Title: Uncovering the structure and the dynamic of information propagation in building design process and product

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THE BENEFICENT AND THE MERCIFUL

Uncovering the structure and the dynamic of information propagation in building design.

Process and product

Thesis submitted in accordance with the requirements of the University of Liverpool for achieving the degree of Doctor in Philosophy

By

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Declaration

The contents of this research are submitted in accordance with the University of Liverpool ordinance 106 for the degree of Doctor in Philosophy in the School of Architecture, Faculty of Humanities and Social Sciences.

None of the research carried out in this thesis has been submitted for another qualification at any seat or institution of learning.

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ABSTRACT

Complexity science has been attracting the interest of researchers and professionals due to the need to enhance the efficiency of understanding complex system dynamics and structure of interactions. Complexity analysis has been used as an approach to investigate complex systems that contain a large number of components interacting with each other to accomplish specific outcomes and develop specific behaviour. The design process is considered as a complex action that involves a large number of interacting components, which are ranked as design tasks, design team, and the components of the design process. These three main aspects of the building design process consist of several components that interact with each other as a dynamic system with complex information flow. In addition, the design product – which is the building – consists of several systems that interact with each other; those systems are the architecture, structure, building envelope, power, and lighting. In this research the goal was to uncover the complex structure and the dynamics of information interactions through the design process stages based on RIBA. In addition, the research aimed to uncover the structure and the dynamics of the building systems interactions. The methodology that was used is a design research methodology; it analysed and modelled the interactions of the design process as a network and accomplished the typology of each design process stage as well as the dynamics of the process from the first stage to the technical design stage. In terms of the building systems design, the networks will modelled the interactions between each building system's components and the components that interact with other systems' components to indicate the typology of the building design product. Moreover, the dynamics of the building design product were applied by modelling the interactions from the architectural spaces to the interactions of the building systems' components. Furthermore, the findings of those interactions were imported into network analysis software to identify measures that indicate the characteristics of the network typology of each building design stage as well as the characteristics of each building system's interaction. In addition, the results highlight the characteristics of the dynamic of the building design stages through the process as well as the dynamic of the building design systems.

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CHAPTER 1: INTRODUCTION

1.1 Introduction

Since earlier times, humans have tended to utilise their ability to generate a design to solve a specific problem. This organising and planning ability is attempted through design action. One of the design problems that designers are facing in this century is accomplishing the design of a functional environment for people's social activities. Thus, architects and designers have been contributing to the field of design from several creative perspectives and approaches. However, the significant contributions to the design knowledge can be enhanced by the utilisation of advanced technologies and theories.

Designing a building requires a series of decisions and dealing with a large number of components, information, design team members, and stockholders. This collection of information, decisions and components is dynamically changeable throughout the process of designing because they interact, connect, communicate and generate flows that form a large number of interactions, which causes an increased level of complexity in the building design process and building design outcomes. This complexity occurs at the level of building design process knowledge diffusion and at the level of building design outcomes, which are the drawings of a building's systems.

Complexity science notions and studies look at complex systems from an analytical point of view to identify the impact of components in one system on another. This view enhances the ability to understand complex systems design as well as to enhance the efficiency of their outcomes. Design complexity is an approach that identifies the complexity within the design and generates a method to achieve solutions to these complex design problems.

In this research, the focus is on how to uncover the complex structure and the dynamic of the building design process by modelling the interactions of the building design process to capture its complexity, based on a case study of a building design process guide. This case study is based on the RIBA plan of work design tasks and design team members who are required to establish these design tasks. In addition, the research will uncover the complex structure and the dynamics of the building design outcomes, which are the architectural layout, structural layout, HVAC system layout, the skin system layout, power system layout, and lighting system layout, to identify by modelling the interactions of the building design components' interactions based on the case study's drawings of an office building.

Using the network analysis software to model the interactions of building design process aspects and the interactions of the building design components, the research will model the complex structure and dynamic of the building design process, and product. Moreover, the use of the network analysis measure will significantly help the research to identify the important aspects of knowledge diffusion in the building design process and the structure of the design process stages. Furthermore, the use of network analysis to measure the networks generated from modelling the building systems components will significantly identify the structure of these systems as well as the ability to assess the design of the systems to be resilient to failures.

1.2 Theoretical background

The background of the study is focused in two main aspects of building design, which are the building design process and the building design product. These two aspects are associated with several complexities in terms of their components' interactions. The building design process comprises a number of actions that are established by the design team to establish an outcome for a building design. These actions are in the form of stages; each design stage consists of a number of design tasks that are assigned to a specific team member to establish in order to move forward in the design process. In relation to the building design product, the word product is defined as "something produced by human or mechanical effort or by natural process" (American Heritage Dictionary); this definition indicates that a product is the result and the outcome of humans' work following a specific process. This indicates that a building can be considered as a product that has resulted from the design process. In addition, according to Vakili-Ardebili (2010), a building is a product because it is the outcome of a of process followed by humans as well as it follows certain regulations and rules that are similar to the process of designing a product. This indicates that a building is a product in terms of its similarity to the product design process and the conditions for which humans design it. Moreover, this explains that the complexity of the product design process can be investigated in the building design process to uncover the complexity within the latter, as well as to enhance the efficiency of the process by determining the factors that can increase the complexity of the design process and the impact that can drive the building design process to more complexity.

Design process Building product

Fig. 1.1 The design process Fig. 1.2 The building design product

1.3 Problem statement

The changes in the functional requirements of buildings has led to the design of large buildings that contain a large number of spaces that interact in accordance to the importance of each space to another in terms of functionality relationships. This increase of functional requirements in buildings design has raised the complexity of designing building systems' layouts. In addition, the increased number of functional requirements has led to an increased number of design team members as well as design tasks, which has significantly increased the complexity of information flow and knowledge diffusion in the building design process. According to Ameri (2008), research has attributed the complexity of architecture and engineering design to complexity of design problem, complexity of design process, and complexity of design product. This has led to the need to model the complexity of both the building design process and building design product using new methods and tools of complexity modelling to enhance the efficiency of their outcomes. The outcomes of an efficient design process require clear modelling and predictions for knowledge diffusion through the design process stages, which will significantly add success to the outcomes. In addition, the outcomes of an efficient building systems design require the building systems design to be resilient to the changes that accrue in the building systems. Furthermore, Alexiou (2009) classified the factors that increase the complexity of defining a design problem, which are mainly the difficulty of determining a procedural process to combat a design problem, and the lack of the right answer to a design problem.

Several aspects in design process literature consider the uncovering of the complexity of the building design process to obtain better design outcomes. These aspects are the approaches of investigating the complexity of the building design process, which are the complexity of modelling the design process, the complexity of establishing the outcomes of the building design process, and the complexity of modelling the information flow and diffusion of knowledge in the building design process. According to Baher Ismail Farahat (2012), the design process needs to be modelled in a logical sequence in order to achieve the goal of the process. This requires a deep investigation of the design process knowledge diffusion and information flow. Moreover, O'Donovan (2003) has developed criteria on which the design process has to be modelled, which are scalability, maintainability, predictability, and robustness. In order to achieve those criteria, there has to be a significant modelling of the information flow between the design tasks and design outcomes and the design team information flow, and a clear vision of the knowledge diffusion in the design process stages. Furthermore, the components or the outcomes of the design process need to be established, as determined in Ralph's (2009) design process model, which models the design process as components that are required to be established. In this research those components are taken into consideration because of the information that flows in the process to establish them. Ralph’s design process components are design problem, design specification, design context, design requirements, design goals, and boundaries of design. Each of the design outcomes is established by the design tasks, which information flows through the design team. The need to investigate the establishment of the design process components or outcomes is raised to enhance the efficiency of its outcomes.

The other perspective of looking at the complexity of building design in this research is the complexity of a building as a product. A building consists of several systems that are complex in terms of their interactions and connectivity. According to Systems (2015), these include the architectural, structural, mechanical, and electrical building systems. The design of these systems requires the ability to deal with complexity in order to achieve resilient systems in several design phenomena. Each of the building systems consists of a large number of components that interact to perform a specific function, so resilience of their design drives the complexity of establishing them to work functionally with the changes and disconnecting of some parts of their components.

1.4 Potential solution

The potential solution of the research problem – which is mainly focused on uncovering the complexity of building design process diffusion of knowledge between design team members in establishing the design tasks and the design components of the process and the complexity of building systems design – is to apply a modelling technique that captures all the components of each building design process and building design product. In addition, the research will investigate and analyse the complexity of the building design process models using the method of social networks analysis to identify the important aspects of knowledge diffusion in each design process stage. Furthermore, it will investigate and analyse the complexity of building systems using the same method of social networks analysis to model and identify the resilience of those systems' designs using the centrality measures to determine the importance of the components of the systems location in the whole design of a building and how this complexity analysis tool significantly helps to assess the resilience of designing building systems.

This research aims to establish a theoretical framework that consists of two main categories of complexity in building design, which is complexity of building design process and complexity of designing building design and systems' layouts. Reviewing the literature on complexity in the building design process and the complexity of designing building layouts, the research will establish a theoretical framework that indicates the factors of complexity in building design in terms of process and product.

Uncovering the structure and the dynamic of building design process factors and designing a building layout will highlight quantitative measures that establish a model that captures that complexity of the building design process, and product.

1.5 Research questions

The main research question is:

What are the structure and the dynamic of building information interaction and propagation in the building design process and product?

The answer to this question requires us to answer several questions that determine the approach to uncovering the complexity of the building design process and product, the reviewing and determining the complexity of the building design in the literature, the tools and the techniques that has been used to uncover the complexity of design, the establishment of a theoretical framework that determines how to model complexity of building design, the establishment of a methodology and a process to be followed to uncover the complexity of building design, the uncovering of the typological characteristics of building design process knowledge diffusion and assessment of its significant aspects, and the uncovering of the typological characteristics of building systems design and assessment of its resilience. Therefore, further research questions are as follows:

1- What is the scientific approach to uncovering the structure and the dynamic of building information and propagation in the building design process and product?

2- What are the factors that increase the complexity of the building design process and product?
3- What are the appropriate tools and the techniques of modelling complexity in the building design process and product?
4- What is the theoretical approach that determines how to model complexity in the building design process and product?
5- What are the typological characteristics of the building design process?
6- What are the significant aspects of knowledge diffusion in the building design process?
7- What are the typological characteristics of building systems design?
8- What are the significant aspects of designing resilient building systems?

The answers to the questions will be found by reviewing the complexity science and theory to determine the tools that are significant in modelling the structure of each building design process stage as well as indicating the dynamics of these stages as the design process moves forward, focusing on investigating the important aspects of knowledge diffusion through the design process. In terms of the product, the answers to the questions will be found by modelling the structure of each building system's design as well as the dynamic of those systems' interactions as the design moves forward to a complete building, focusing on assessing the resilience of each system design using the complexity analysis tool.

1.6 Aim and objectives of the study

1.6.1 The research aim

Principally, this research hypothesis is that the use of complexity science tools can significantly help improve the design of buildings from the two perspectives of the design process and the design product. The improvement of the building design process focuses on analysing the diffusion of knowledge through the design process stages, and the improvement of the building product design is focused on making building systems resilient to the changes and the phenomena that can accrue in them. The aim of the research is to uncover the structure and the dynamic of case studies for both the design process and the design product using the network modelling tools. The information generated will help to improve ideas relating to understanding the diffusion of knowledge in the design process, and the design of buildings to be resilient.

1.6.2 Objectives of the research

The focused aim of the research is to use a complexity analysis tool, which is network analysis, on the building design process and the building systems design to help understand knowledge diffusion in the process and resilience of a designed building product. The objectives of the study are listed below:

1- Modelling the interactions between the three main aspects of the building design process, which are design tasks, design team, and design components, in a form of networks; each stage is an independent network characterised by its typological findings.

2- Identifying the significance of the design process components and the design team members in terms of knowledge diffusion through the design process using the design process stages' network models.

3- Modelling the interactions of building components of the architectural, structural, envelope, HVAC, power, and lighting systems in a form of network for each system that is characterised with its typological findings.

4- Assessing the building systems' design in terms of their resilience to certain phenomena that are significant in designing building systems using the building systems' network models.

1.7 Research process

The research process followed in this research is based on the complexity science tool of modelling, which is the network analysis modelling. The method of modelling the interactions between the design processes and building systems design is followed in three steps. The first step is determining the interactions between the aspects of the process, such as a design team member and design task, or determining an interaction between two components of a system using the design structure matrix for the design process and extracting data from the building drawing to build the system. Second, importing the data to a network software analysis program, Gephi, and building the typology of each network imported. Third, running the results of the components by using several measures that can interpret the knowledge diffusion in a network or that can assess the resilience of a network. The methodology is explained in detailed in Chapter 5.

The research process consists of five main stages, as listed below:

1- Reviewing the literature on complexity science and complexity analysis tools.
2- Establishing a theoretical framework of complexity in the building design process and building as a product design.
3- Extracting data from case studies.
4- Data analysis.
5- Assessing the findings of the networks based on the focus of studying knowledge diffusion in the design process and the resilience of the building systems design.

1.8 Thesis outline and structure

The flowchart in Fig. 1.3 illustrates the structure of the thesis, and the content of each chapter is outlined below:

Chapter 1 provides an overview of the research including the introduction, the theoretical background, problem statement, potential solution, and research question, aims and objectives of the research, the methodology applied for the research, and the research process.

Chapter 2 provides an overview of the complexity theory and the various viewpoints in relation to complex systems. In addition, it will provide an overview of the literature on complexity in design and in building design.

Chapter 3 provides an overview of several tools and techniques that have been used in the literature to analyse and model complexity of design by reviewing several research papers on the complexity of the design process and design product. In addition, it will review the literature on the tools that will be used to analyse the complexity of the building design process and building systems design, which are the network modelling techniques and measures.

Chapter 4 provides a theoretical framework that focuses on modelling the factors that increase the complexity of the building design process and building systems design. In addition, the chapter will present a method of modelling the information flow and knowledge diffusion in the building design process as well as a method of modelling the interaction between building systems' components.

Chapter 5 provides an explanation of the methodology applied in the research as well as the research process in order to achieve the goal of uncovering the complexity of the building design process, building architectural design, and building systems design. In addition, it indicates the methods and the process that will be followed to model the complexity of the process and building using the network software modelling and the network measures to analyse the complexity of design.

Chapter 6 provides an analysis of and measures the building design process complexity using the case study of a RIBA plan of work to model the knowledge diffusion and information flow between the design process's three main aspects: design tasks, design team, and process components. This modelling will result in a form of networks of information flow and knowledge diffusion for each of the design process stages, which uncovers the structure, and the dynamic of it.

Chapter 7 uncovers the typological characteristics of several aspects of complexity in designing a building's architectural layout using a building design case study. This chapter will uncover the structure and the dynamic of building architectural layout design as well as assessing several important aspects of designing a building layout, which are the assessment of the functionality of the building layout, building resilience into fire escapes, and assessment of way finding using network modelling techniques and measures.

Chapter 8 uncovers the typological characteristics of several aspects of complexity in designing a building's structural system using a building design case study. This chapter will uncover the structure and the dynamic of building structural design as well as assessing several important aspects in designing building structural systems, which includes assessing the building structural system's resilience to disconnection of structural components of the system.

Chapter 9 uncovers typological characteristics of several aspects of complexity in design building systems such as envelope system, HVAC system, power system, and lighting system using a building design case study. This chapter will uncover the structure and the dynamic of building systems design as well as assessing several important aspects in designing building systems, which includes assessing the building system's resilience to failure of components of the system.

Chapter 10 provides the findings of the study in relation to the literature of complexity analysis and measures in design. It indicates the theoretical framework findings of factors that increase complexity in building design as well as indicating the findings of the typological characteristics of modelling the process and the building architectural design, and building systems design. In addition, it indicates the significance of the use of network modelling to assess knowledge diffusion in the building design process, and the resilience of building systems design.

Chapter 11 summarises the thesis, indicates the contribution of the research, highlights its limitations, and discusses the opportunities for significant further research.

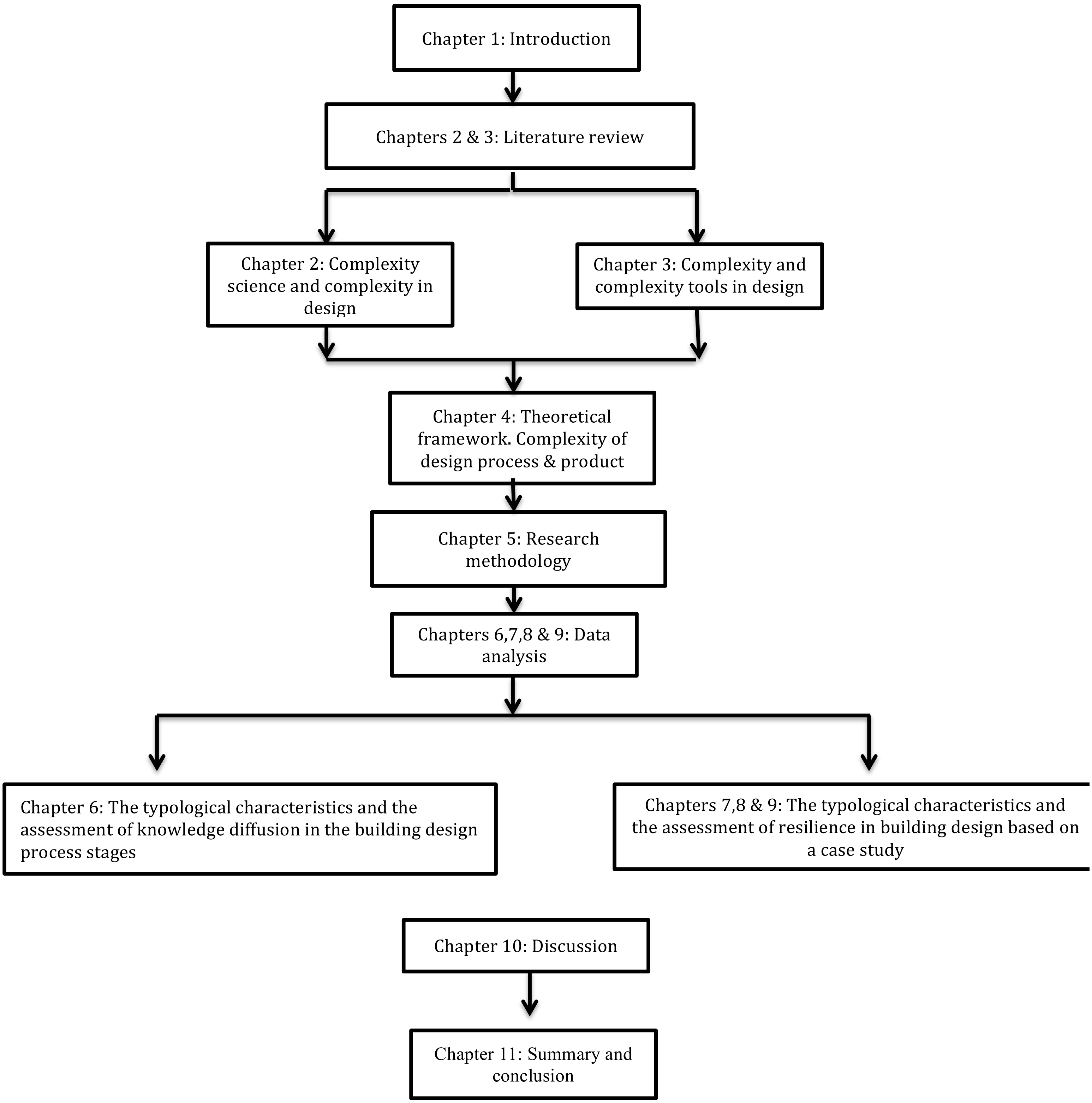


Fig. 1.3 Structure of the thesis

CHAPTER 2: COMPLEXITY SCIENCE AND COMPLEXITY IN DESIGN

2.1. Introduction

The notion of studying complex systems and the complexity of the interactions of their components has been attracting the interests of researchers and professionals due to the need to enhance the efficiency of complex systems' performance in the natural world as well as in the technological industries such as architecture, engineering and medicine. Therefore, this chapter will concentrate on reviewing the literature on complexity theory, definitions of complex systems and the various views of scientists and researchers that define complex systems and complexity theory and determine the complex system classification. In addition, the chapter will present the characteristics of complexity in complex systems in general and in design. The first part of the chapter will introduce the complexity theory and science and compare the different views of what complex systems are and what complexity theory can do to enhance our understanding of them. The second part of the chapter will introduce the literature of complexity studies in design.

2.2 The complexity science and theory overview

2.2.1 Complexity definitions

According to the Cambridge Dictionary, complexity is "*the features of something that make it difficult to understand or find an answer to*" and complexities is defined as "*the state of having many parts and being difficult to understand or find an answer to*" (Cambridge Dictionary). In the previous definitions of complexity and complexities, complexity was described as the features of something, whilst complexities were defined as the state of having many parts. This means that describing something with complexity can be either describing its features or components' interactions, or that its particular condition is complex. Both definitions characterise the components and condition of complexity as containing difficulties that need to be understood. The Oxford Dictionary's definition of complexity is "*the state or quality of being intricate or complicated*". This definition explains that the state of complexity is complicated. As a result, complexity can be described as a collection of interacting components in a complicated condition that is not understandable.

According to Johnson (2009), complexity is not easy to define because, when looking up the word complexity in dictionaries, it was defined as "*the* behaviour *shown by complex systems*"; however, the definition of complex systems is "*A system whose* behaviour *exhibits complexity*". This means that the definitions of complexity and complex systems vary and each has different meanings. As a result, there is not a clear definition of complexity, but it can be described as a notion of studying complex systems in scientific research by using several examples of real-world systems. In addition, complexity has been described as "Two's company, three is complexity", which indicates that complexity is a combination of more than two components that form a system. Furthermore, what can be specifically defined is complexity science, which has been defined as "*a study of phenomena emerge from a collection of interacting objects*" (Johnson 2009).

The previous definition explains that complexity science is the study and observation of a certain phenomenon that happens from interacting objects. This means that objects are simple, but when they combine in a sort of system environment, they form complex interactions. Those interactions will lead to certain phenomena characterised by complexity. Complexity science focuses on studying the complication of objects' interactions in certain phenomena. The combination of system components is an example of such an emergent phenomenon, which occurs when a group of components combines. Those components operate together as one system, which forms complexity. Furthermore, complexity science studies the interactions between the components of complex system as well as the phenomena that emerge from these interactions. For example, the complexity that emerges from the interaction between buyer and sellers in a stock market can be described as phenomena that emerge from a competition of supply and demand. Understanding complexity science will help to understand and predict events that happen from emergent phenomena in complex systems.(Johnson 2009)

Clearly, systems can be managed and controlled from a coordinating point of systems. However, with regard to the phenomena that emerge from complex systems, they emerge without the need of coordinating points. This sort of phenomenon is indicated in the self-organisation of complex infrastructure projects such as the movement of pedestrians or traffic. The complex highway systems indicate an example of self-organisation of cars during the rush hours. The phenomenon of a traffic jam emerges when lots of cars compete on locations in the street. This explains self-organisation of cars as objects in the highway system and how the cars organise traffic without a coordinating point or central control of the whole highway system. The description of complexity indicates that it is a characteristic of a phenomenon that occurs when more than three components interacts. The study of these interactions is complexity science (Johnson 2009).

2.2.2 Aspects of complexity in complex systems

In order to define complexity, complexity-related terms have to be defined, such as complex systems. When looking specifically at the term complex systems, Simon (1962) defined it as "*one made up [of] a large number of parts that interact in a non simple way*". This definition describes a complex system as containing several components that interact with each other. These interactions, which take place between the complex system's components, do not interact in a simple way, but in very complicated interactions. In addition, the definition describes complexity of complex systems as having four aspects. Those sections are aspects of complexity where complex systems and complexity take a place in those aspects. First, complexity taking the form of a hierarchy: this hierarchy is formed in terms of the complex system's interactions, and the subsystems that the complex system contains, which results in a complexity hierarchy between the complex system, its subsystems, and their interactions. The second aspect compares a hierarchical system to a non-hierarchical one in terms of the time taken for them to emerge, which means the time needed for a complex system to operate and function. The author argues that a hierarchical system will emerge faster than a non-hierarchical one if both systems are of equal size. The third aspect is that the complex hierarchical system is characterised by a dynamic ability to simplify its subsystems in order to understand their behaviour. Finally, a complex system has the ability to examine the relation between a complex system and what it contains, such as subsystems and interactions (Simon 1962). An analysis of the previous four aspects of complexity and complex systems can lead to a more specific definition of complexity if looking at complexity and complex systems separately, by characterising complexity as relating to hierarchy and complex systems to subsystems and interactions (connections). The first aspect indicates the ability to understand that complexity is a hierarchy of a large number of complex systems with each complex system containing subsystems and interactions (connections). The second aspect focuses on the time that hierarchical systems need to emerge (operate and function), and argues that a hierarchical system emerges quicker than a non-hierarchical one, which explains that hierarchy emergence in a complex system can be expected in terms of time taken to operate and function. In relation to the third aspect, a complex system can simplify its components dynamically to understand their behaviour, which indicates the methods and analysis of the complexity of a complex system, subsystem and interactions in terms of its behaviour, such as how it operates and functions, as well as how functional and operating problems can be solved. The fourth aspect is the ability to examine the behaviour of a complex system and its components individually. This divides the complex system in terms of its subsystems and its interactions to determine specifically what part of the system needs to be examined, either the whole complex system, subsystem or an interaction point, as well as it simplifies the ability to study and analyse the complexity of the whole system.

As a result, the four aspects of complexity and complex systems in the previous research can lead to clear definitions of complexity and complex systems. However, do the definitions describe complex systems and complexity separately? This question raised by Johnson (2009) at the beginning "*Simply complexity*" book. In addition, the definition in "*Simply complexity*" defines the study of complexity science. However, the information for the previous four aspects characterises and defines complexity as a hierarchy between dynamic components, which needs a certain time to emerge and be able to simplify and examine its behaviour. In addition, it defines a complex system as one that contains several emergent subsystems that have the ability to simplify its context in order to examine its behaviour.

2.2.3 Types of complexity in complex systems

Sussman (2002) wrote a paper reviewing several definitions of complexity and complex systems in the literature. It also explains the use of complexity in domains and the various ways in which complexity terms were applied in each field. In this paper, a system is defined as "*complex when it is composed of a group of related units (subsystems), for which the degree and the nature of the relationships is imperfectly known*" (Sussman 2002). In addition, complexity is an emergent behaviour of one or more complex systems that is difficult to be predicted, even if the subsystems' behaviour and the interactions can be predicted and known. Furthermore, the paper divides complexity of complex systems into three types. First, behavioural complexity means that complex systems, subsystems or interactions contain an emergent behaviour that is usually not simple to predict before or after the fact. Second, internal: the structure of this type of system is very difficult to change without a failure in the system. Third, evaluated: this type of complexity happens when the team of experts and designers of the complex system have different decisions in the design, which will make the design process as well as evaluating the behaviour of the system complex.

The previous types of complexity listed in the paper "Collected Views On Complexity In Systems" (Sussman 2002) defined a system with keywords recognising the complexity of complex systems' definitions in the literature, such as composed, group, units, and subsystems. In addition, the previous literature has sorted significant characteristics in the complexity of complex systems into behavioural, internal, and evaluated complexity. Behavioural complexity focuses on the system's behaviour, such as phenomena that can emerge without a prediction and cause a change in the system. This type of complexity is very significant to observation of a complex system's behaviour in order to predict the future of the system's emergent phenomena. Internal complexity means that the changing of any of the system's components will cause a failure due to the complexity of the system's structure. This type of complexity focuses on studying the structure of a complex system, as well as on understanding the content of the system, such as the structure of the whole system, the structure of the subsystems, and the structure of the connections between the systems. Evaluated complexity is in the early phases of the system's design, so it is a complexity that relates to making decisions – either a component should be designed and placed in a certain condition, or it should not. The previous types of complexity defined complexity as *unpredicted behaviour of a group of composed systems and subsystems structured in a way that is difficult to change and design*.

In addition, Wilson (1999) stated that the greatest challenge of complexity is not studying the cells of biology but it how to incorporate complexity theory in all fields of science to enhance their description as complex systems. Furthermore, the explanation looks at the great challenge to scientists to reassemble a complex system that has been divided because of the task, which will enhance the researcher's ability to predict the complex system's emergent phenomena, especially when it moves from complex to a more complicated phase. In addition, Wilson (1999) defined complexity theory as *"the search for algorithms used in nature that display common features across many levels of* *organization*". He believes that complexity theory may lead to new exploration in emergent phenomena fields such as ecosystems, cells, and brains.

As a result of Wilson's (1999) definition, complexity is defined as the result of restructuring a complex system for the purpose of studying a complex system and its components in a way to predict its emergent phenomena. More information can be reached when restructuring is more detailed. Wilson defined complexity as a mathematical search, so a complex system can be defined as mathematical relationships between the components of a system. Complexity can be defined as the study of mathematical relationships between components by breaking down their system into parts and then restructuring it.

Furthermore, there are lots of definitions of complexity in the literature; some definitions describe complexity according to the system's behaviour, and others focus on the structure of the system's components. However, dictionary definitions point out two features of complexity, which are interconnections of a system's parts and the nature of the interconnections. Moreover, described important views of complexity. These views are important in expanding complexity to increase functionality, efficiency and flexibility (Sussman 2002). As a result, one of the important features of complexity is the interconnections of a system's parts and the environment of the interconnections. Furthermore, in order to enhance the functionality and the efficiency of a system, the level of complexity needs to be increased by expanding the interconnections.

In "*The Art of System Architecting"*, the word complex means, "*composed of a set of interconnected or interwoven parts*" (Maier 2000), and a system means "*a set of different* *elements so connected or related as to perform a unique function not performable by the elements alone*" (Maier 2000). In general, this definition agrees that increasing complexity is the most important challenging idea facing engineering and architecture.

2.2.4 Ways of investigating complexity

Complexity science is "*a study of a phenomena emerge from a collection of interacting objects"* (Johnson 2009). Complexity science brings very various ranges to study contemporary science, especially the management and organisational domains. This has led to no clear agreement about what complexity science is. However, several schools in the field have determined three directions in which to investigate complexity in different methods and strategies; these views are shown in Fig. 2.1. First of all, "Reductionist Complexity Science", which is related to every theory in physics; however, it is not necessary that this science answer all of the questions in it. The community of this science seeks to find out the principles of complex systems in nature, in order to answer the questions of the field. In addition, it focuses the physics aims on reaching results by embracing algebra. This type of complexity science is based on an interesting method of logical measure, three promises. One is a mathematical rule applied in computing to give complex patterns. Second, the world in complex patterns that can be studied the same as the computer science rules. In conclusion, the simple rules can be found out by studying the phenomena in the world using computer science (Cilliers 2001).

The second view is "The Soft Complexity Science", which sees complexity concepts as an idea of organisations. It looks at complex systems in terms of the concepts of connectivity, edge of chaos, emergence, landscape, etc. The idea is that social science is a very interesting study as well as different from studying natural world. For example, the theory and the language in complexity science that have been applied in the natural world do not examine its social aspects, even though the language of natural science is similar (Cilliers 2001). The third is “Complexity Thinking”, which is the most well known in the complexity literature. This school involves philosophical study in the field of managing. If a study assumes that a type of organisation is considered a complex system, then the limits and the profession and nature of the system has to be recognised (Cilliers 2001).

However, one drawback with the previous types of complexity school is that they do not answer the question of what complexity science is. It actually sorts the types of schools in complexity science, which is very important to be determined in order to understand complexity. Therefore, reductionist complexity science looks at the exact complexity of physics and how things in nature behave. However, the focus point in this research is the soft complexity science that studies the concepts of interacting objects in a complex system.

In addition, complexity theory has been defined as *“Complexity theory is studying complex social phenomena is promising because of its focus on understanding relationships between and among individuals, organizations, and/or systems, and resulting collective behaviours and outcomes”*(Trenholm 2012). This definition describes soft complexity science as a study of complex systems and organisations as well as studying the individuals. Those three schools of thought determine the complexity study in this research in terms of investigation of the individual components of a complex system and subsystems, and studying the organisation of the interactions between the system and subsystems to predict the outcomes of the whole system.

In addition to the three directions for investigating complexity, Braha (1998) has determined a significant direction for investigating complexity from a design point of view that mainly focuses on engineering systems. According to Braha (1998),"*the complexities of design process or design product substantially influence their performance*". This indicates that there is a complexity in the design process from managing the process perspective and complexity in the product, which significantly emerges as a complexity of performance. This has led to a fourth type of investigating complexity, which is engineering complexity.

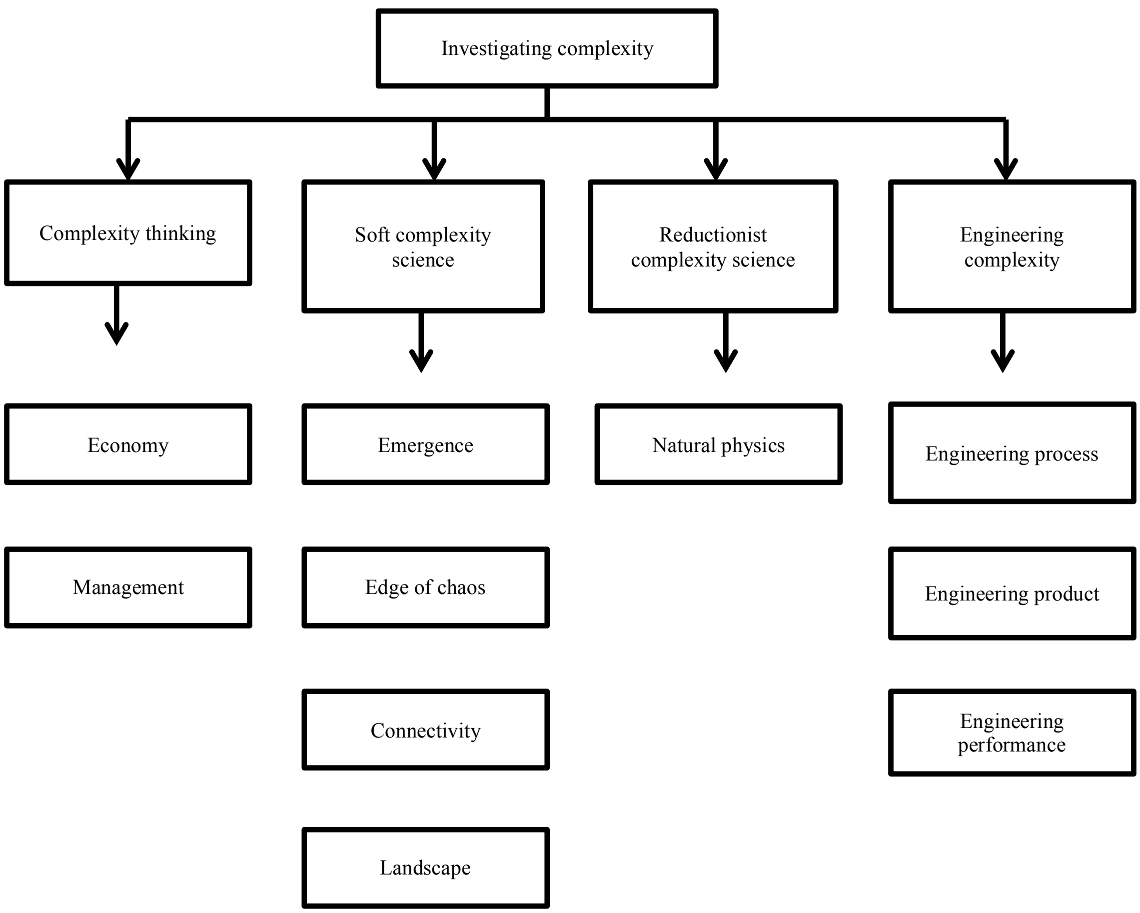


Fig. 2.1 Three types of complexity science schools and the domains involved in each

2.2.5 Principles and characteristics of complex systems

There are several views in the literature that characterise the complexity of complex systems as well as determine the characteristics of their complexity. This section of the research will review the literature on complexity principles and characteristics. In order to determine the principles and characteristics of the complexity of complex systems, the terms need to be defined. According to (Oxford 2014), the word principles refers to "*A fundamental quality determining the nature of something*" and characteristics means *"a feature or quality belonging typically to a person, place, or thing and serving to identify them"*. The previous definition explains that principles are the quality that determines that nature of the complex system's complexity; in other words, it determines the complexity principles that define a system as a complex system. In addition, the second definition explains that the characteristics of something consist of the features that identify it.

2.2.5.1 Principles of complexity in complex systems

According to Webb (2004) in "The secret of the six principles", there are six principles of complexity in complex systems. These principles are the fundamental qualities that characterise the complexity of complex systems. They help to improve the ability to understand complex systems as well as enhance the ability to achieve a strong analysis of them. These principles are self-organisation, diversity, history and time, unpredictability, pattern recognition, and the edge of chaos, which have been descried as the six core complexity science principles.

2.2.5.1.1 Self-organisation

Self-organisation is defined as "*the ability of a system to spontaneously arrange its* *components or elements in a purposeful manner, under appropriate condition, but without the help of an external agency*" (Dictionary). This indicates that this principle of complexity is focused on the system's ability to manage and arrange its components without the need for external action. This describes that self-organised system behaviour emerges without the need for a coordination point or central control. This emergence explains the behaviour and the interactions of a complex system in the system's environment. Through those interactions a certain level of unpredictability of emergent phenomena happens due to the interactions. Most importantly, there are no actual components in charge of this emergence; it happens with no predictability. In other words, there is no connection between the event happening and the results of the event. This is called self-organisation of emergent phenomena, which is characterised by lots of interactions between the components of a system, and none of the components are aware of the whole interactions (Webb 2004).

According to Johnson (2009), the self-organisation of complex systems has four significant characteristics. First, there is no prediction of the system's emergent phenomena. This means phenomena can emerge with no exact predicted time, or information, or consequences. Second, the phenomena of a complex system emerge without the need for a coordinating point. This can be explained as self-organisation of a complex system. Third, complex systems are characterised by their ability to change and be changed by their environment. Fourth, the system is coordinated or managed in an organised condition. The organisation of the system is far from balanced and similar. Moreover, Cilliers (2002) described the self-organisation of a complex system as having two significant characteristics. First, the system is coordinated or managed in an organised condition; this type of organisation of the system is far from balanced and similar. Second, the complex system's components are not fully aware of the whole system's behaviour; therefore, they respond to the information received locally. Mitchell (2009) agreed that self-organisation of complex systems is characterised by "complex collective behaviour", which means that all the complex systems in different domains are operating and function with no coordination point or central control. And it is very difficult to predict the behaviour of a complex system or determine a certain pattern to it. Heylighen (1989) stated that self-organisation of complex systems can certainly be coordinated. This coordination can be modelling in a network consisting of interacting components to understand the system's behaviour. In addition, Alexiou (2009) characterised complex system self-organisation as having four significant aspects. First, the agents of complex system control point are distributed not centralised. Second, the degree of freedom given to the system components' behaviour determines the degree to which the system can self-organise. Third, when the level of the uncertainty of system behaviour increases, the system becomes chaotic. Fourth, complex system behaviour emerges from the interactions of the agents.

2.2.5.1.2 Diversity

Diversity is defined in the Oxford Dictionary as "*a range of different things*". This explains that diversity is a collection of different components of a complex system that can be characterised by complexity. In addition, an example of a diverse system is an ecosystem; the diversity of the ecosystem opens up the possibility for the system to adjust and organise itself when a certain problem happens. Diversity plays the role of finding options to solve problems in a complex networks (Webb 2004). A diverse complex system *consists of several types of components that interact with each other*. The components are organised according to the relations between them, such as physical connection, information exchange, or part of a one system component (Johnson 2009). The previous characteristic indicates that there is a range of diversity in components as well as in interactions in system components. In addition, Cilliers (2002) described the diversity of complex systems as having two characteristics. First, a complex system contains a large number of components, and the level of the system's complexity increases as the number of components increases. Second, the large number of components has to interact with each other dynamically. This interaction can be physical or informational. Moreover, according to Heylighen (1989), a complex system consists of diverse interacting agents and interacting methods.

2.2.5.1.3 History and time

Feedback is defined as "*the modification or control of a process or system by its results or effects*" (Oxford Dictionary). This definition indicates that receiving feedback from a complex system will occur by looking at the results or the previous behaviour to predict the future behaviour. Moreover, feedback is one of the important aspects that affect and determine the complexity of a complex system. Scientists have explained that a complex system's feedback is the historical knowledge of the system that can be determined in order to enhance the system's performance (Webb 2004). In other words, in order for a system to sustain and operate efficiently, it needs to receive feedback about its performance. Johnson (2009) described complex system feedback as having four characteristics. First, the components of a system interact with each other and make a respond to the future according to previous information. This means they use information from the past to make decisions in the present. In other words, specific feedback from a complex system can change the system's behaviour. Cilliers (2002) agreed that complex systems rely on their history to determine their behavioural actions in the future. Second, the previous information (feedback) of the components of a system determines the components' ability to adapt another system. The components of a system can adapt its behaviour according to its feedback, thus adapting to improve their efficiency (Johnson 2009). This what Mitchell (2009) described as *"signalling and information processing"*, which is exchanging information through a complex system's internal and external environment? In other words, these systems interact with their environment and send and receive information to determine their behaviour. Third, complex systems are "alive". The system improves in a complicated way, and interacts and adapts according to its feedback. Fourth, complex systems are characterised by their ability to affect and be affected by their environment. For example, a market can be affected by outside news that either makes positive or negative changes. In addition, a company price can be affected by its news, which can also affect other companies in the market. In another example, maintenance to a road can cause traffic jam on one or more roads. Finally, the feedback between the components can be received directly or through a number of interventions (Cilliers 2002).

2.2.5.1.4 Unpredictability

According to the Oxford Dictionary, unpredictability is *"not able to be predicted; changeable"*. There are a lot of interactions in a network environment that are not very easy to understand or predict. For example, unknown behaviour and the place of a component in a network can cause a very important event or a phenomenon that changes the system's behaviour. And the difficulty is to determine and understand the behaviour of the component in order to predict the event (Webb 2004). Heylighen (1989) stated that non-linearity of complex system interactions causes unpredictable behaviour of the system's outcome. In addition, the complex system is a combination of organised and predicted behaviour, and unorganised and unpredicted behaviour. Furthermore, the systems are open in a way that the interactions between them and their environment are difficult to determine (Johnson 2009). In addition, a complex system's interactions with its environment is difficult to determine (Cilliers 2002). Moreover, according to Alexiou (2009), the behaviour of complex system agents follows rules and laws, but it is not completely determined because there is an alternative behaviour that emerges locally and which is not predictable. In addition, determining the predictability of a complex system and centrality can be the reasons for the system to become a linear system and prevent the system from self-organising and adapting and adjusting to its environment.

2.2.5.1.5 Pattern recognition

The word pattern is defined in the Oxford Dictionary as "*an arrangement or design regularly found in comparable objects*". This definition describes that the patterns of complex systems consist of several components and several interactions. Moreover, there are two types of patterns in complex systems. First, the pattern of the components; this means that the components are connected to each other in a specific pattern. Second, the pattern of interactions: this is the pattern of the interactions or the connections between components of a complex system.

"*The more complex the network is, the more complex its pattern of interconnections, the more resilient it will be*" (Webb 2004) The word pattern usually suggests the idea that there is an organisation to several components that form recognised relations. However, understanding how a whole system of interactions works entails perceiving the pattern of interactions between the components. For example, looking at a dynamic system, it is a group of components that form a pattern of interactions, and the more complex the complex system the more difficult it is to predict its pattern. In addition, when the behaviour of a complex system is not predicted, the pattern of the components or the interactions will be unpredicted (Johnson 2009). Moreover, (Johnson 2009) characterised the complex system pattern as having two significant aspects. First, the interactions of the components characterised by non-linearity. This indicates that the pattern of a complex system's interactions is non-linear. Second, components of a system are in a short-range of interactions. This indicates that the connections between components of a complex system are in a small distance. Cilliers (2002) described the pattern of complex systems as having three significant characteristics. First, the behaviour of one or more component changes the pattern of the complex system. Second, the interactions of the components are characterised by non-linearity, which indicates that the pattern of interactions is non-linear. Third, the pattern of interactions between the complex system's components is in a short range of interactions. Alexiou (2009) described the pattern of a complex system's components with non-linearity of interconnections between components; these interactions are strong, weak, or non-interacting.

2.2.5.2. Characteristics of complex systems

According to Cilliers (2009), technology has enhanced our opportunities to understand science. And one analysis tool for complex things is to take the whole system and divide it into units that can be understood and connect them together. However, the study will not determine the dynamical part of the system. In addition, Cilliers (2002) agreed that there is no clear definition of complexity; however, complexity can be defined by the characteristics of a complex system. Furthermore, this has determined the difference between simple and complex. A system can appear to be simple by the complexity of the system is happening when components interact. This interaction forms the system's complexity.

According to Johnson (2009), the term complexity characteristics are a description of a complex system and its components in terms of their behaviour. In addition, Cilliers (2002) characterised complexity with aspects that agreed with Johnson (2009). However, Johnson's description focuses on the complexity of system behaviour and system components, whereas Cilliers' description focuses on the aspects of the complex system and how it interacts and behaves in its environment. In addition, Mitchell (2009) described the common principles of a complex system, which determine its behaviour and interactions. Moreover, Heylighen (1989) characterised the interactions of complex systems and differentiated between the complex system and the chaotic system.

The previous literature indicates significant characteristics of the complex system, as shown in Fig. 2.2, which can be summarised into systemic characteristics, interactional characteristics, and behavioural characteristics. The systematic characteristics are indicated in a large number of components that interact with each other. The interactional characteristics are indicated by the dynamic, physical, informational, and non-linearity of the relations among the system's components. The behavioural characteristics are indicated in the system's complex behaviour.

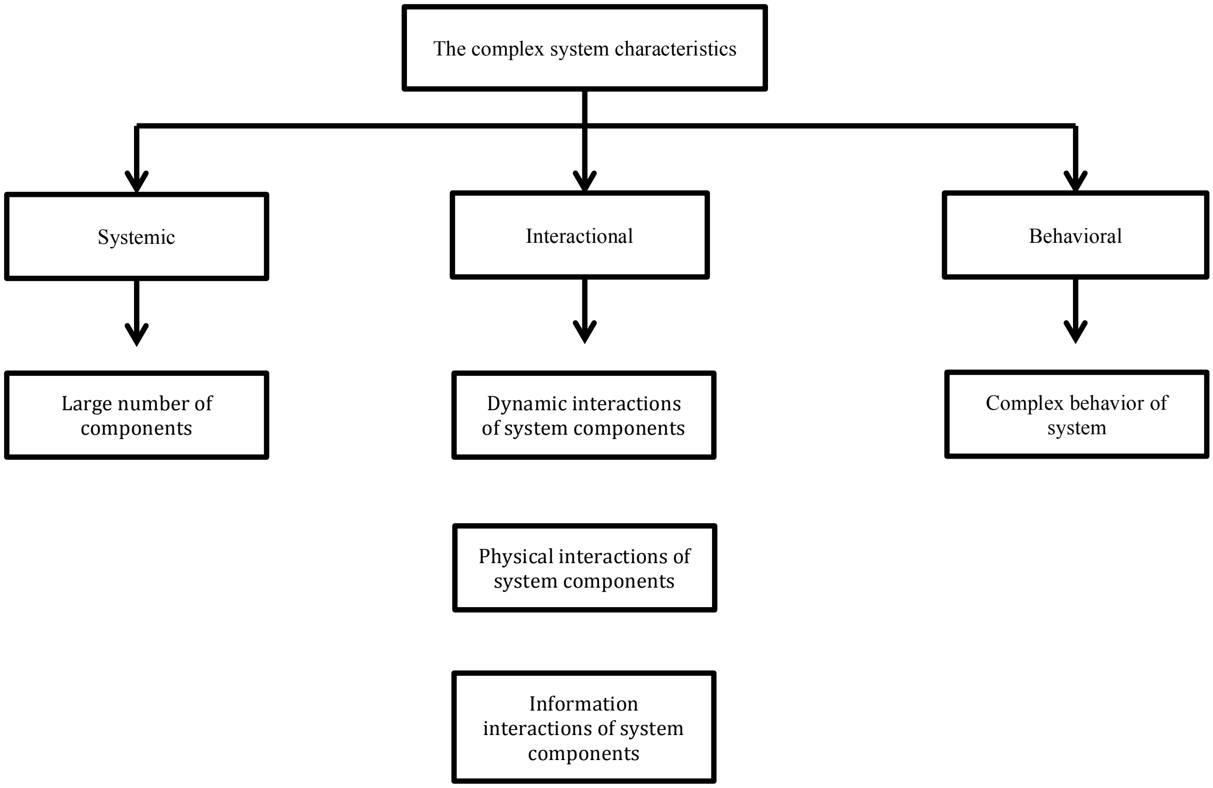


Fig. 2.2 Complex system characteristics

2.3. Reviewing the complexity in design

This part of the chapter will review the significant literature on design complexity going through the overviewing of the term design. In addition, this section will highlight the studies on design process and design as a product, which are the main aspects of this research, which will uncover the complexity of their structure and the dynamic of its information interactions and propagation of its aspects and components. Moreover, the section will review the literature on complexity in the building design process, and building product design.

2.3.1 Design definitions

The term design is used in different fields such as architecture, engineering, art, etc. Generally, the word design has two meanings in the fields of architecture and engineering. First, design as an object or a product, which are the final outcomes of the design process. Second, design as a process, which is the art and actions performed by designers or individuals to achieve the final product or the object, such as buildings and drawings.

The Cambridge Dictionary defines design as "to make or draw plans for something, for example, clothes or buildings". In addition, the Oxford Dictionary definition of design is "a plan or drawing produced to show the look and function or workings of a building, garment, or other object before it is made". The Cambridge definition describes the term design as a number of processes taken by a designer, such as making a drawing, following several steps to achieve a final product, for example, a building. However, the Oxford Dictionary definition defines design more specifically, as the final outcomes of the process, which is "A plan or drawing produced to show the look and function or workings of a building, garment, or other object before it is made".

The Dictionary of Contemporary English offers several definitions of design, such as "process of planning", "arrangement of parts", "pattern", "drawing", and "intention". These are the main definitions in this dictionary, and they contain the significant terms when describing design as a process or a product. The "Process of planning" is described as "the art or process of making a drawing of something to show how you will make it or what it will look like" (Procter 1981). This definition explains that design consists of the process of drawing or actions that have to be taken by designers to result in a specific object's appearance or shape. The second aspect is the "arrangement of parts", which describes design as "something that has been planned and made, including its appearance, how it works". This definition explains that the design of an object consists of components organised or arranged in a specific way; this definition includes the function and appearance of the components. The third definition describes design as a "pattern", which means that it is a pattern of components that form an object. The fourth definition is "drawing": "a drawing that shows how something will be made or what it will look like" (Procter 1981). Describing design as a drawing means that drawings are the final outcome or the final object of the design process.

There are several definitions in the literature that defines design as a process and as a product. Design as a process is defined as "fundamental soul of a man-made creation that ends up expressing itself in successive outer layers of the product or service" (Jobs 2000). In addition, "the process of defining the architecture, components, interfaces, and other characteristics of a system or component" (Bourque 2004). These definitions indicate that the term design is used to refer to the process of making or explaining the final product, such as a building, as well as referring to the process of making and explaining the product's parts. Moreover, the arrangement or the action of designers in designing parts of the whole product and linking them together to make a final product is considered as design as a process, which is indicated in the following definition: "Design means to map out, to plan, or to arrange the parts into a whole which satisfies the objectives involved" (FitzGerald 1987). Finally, the definitions that describe design as a process and the process of making and arranging its parts are: "Designing is creating a structure that organizes the logic in the system" (Beck 2000), and "Design is a general term, comprising all aspects of organization in the visual arts" (Richardson 1984). Moreover, it is "The process of inventing physical things which display new physical order, organization, form, in response to function." (Alexander 1964). "Design is, in its most general educational sense, defined as the area of human experience, skill and understanding that reflects man's concern with the appreciation and adaptation in his surroundings in the light of his material and spiritual needs" (Archer 1979).

The previous definitions indicated that design, as a process is the process of making or describing or defining an object that will be built to satisfy specific requirements. Design as a product is indicated as the final outcomes of the design process and the product or the object itself. The definition that will be used in this research for design as a process is "a specifications of an object, manifested by some agents, intended to accomplish goals, in particular environment, using a set of primitive components, satisfying a set of requirements, subject to some constraints" (Ralph 2009).

2.3.2 Design complexity

The need to identify the complexity within an object or a product's design will significantly enhance the efficiency of the design process as well as the outcomes of the design. Ralph's (2009) design model identifies the components of the design, which will logically contain complexity in two dimensions. The first dimension is the complexity within each component of the design, such as specifications, agents, goals, requirements, primitives, and constraints. The second dimension is the complexity of the whole, which is the complexity of the interactions and the connectivity between the components of one system, which is the design process connectivity. In addition, complexity of design can be defined as "the measure of uncertainty in understanding what it is we want to know or in achieving a functional requirement” (Suh 2005). This definition indicates that complexity of design can be determined and captured once the designers have identified the uncertainty that is built into each of the design components in Ralph’s model. In addition, defining the uncertainty within the process of the whole design and the complexity of interactions between those components needs to be measured mapped and predicted. Moreover, Alexiou (2009) describes design complexity as an “indeterminism problem because it lacks the knowable complete set of beginning condition owning to endless amount of information that can be collected before beginning”. This definition specifically identifies that there is complexity in each component of the design. It explains the complexity of design components as an undetermined problem due to the inability to completely know the solution to it, as well as the large amount of design information that flows between the design components in order to achieve the final design, which causes increasingly complexity in the design.

In relation to architecture and engineering design, Ameri (2008) analysed and measured complexity in three main classifications, which are complexity of design problem, complexity of design process, and design product. In addition, the research indicated that the complexity within the design problem is in the components of the design problem, which are the requirements, needs, functions, and objectives of the design. And the complexity within the design process is founded in the steps that are taken to find a solution to the design problems, which are the previous components. Complexity in the product design is not specifically defined in this research; it was described as the complexity of the product, which is the result of the process.

According to Braha (1998), “the complexity of design process or design product substantially influences their performance". This study indicates that the study of complexity in design has to take the impact of the process on the product into consideration, which therefore will influence the performance of the product.

The previous studies do not capture the complexity of making or designing a product. It captures some parts of the complexities within the design. However, there is a need to define the complexity in design as a whole, which will work as a guide for designers, and individuals who are involved in the design to identify what complexities they are facing as the design process moves forward. This research will classify the complexity of design with the aim of capturing the complexities in the design process, and with buildings as the product. It will focus on studying the complexity in each design component as well as the complexity of all the design actions and arrangements and process to the final product. This study will look at the design of a product as a dynamic system where each component impacts on the other one.

This research classifies the complexity of design into two main aspects, which are the complexity of the building design process and the complexity of the building product design. There is a clearly significant fact that indicates that both classifications of complexity in design are connected and influence each other in relation to the efficiency of the product's performance. This is clearly highlighted because the components of the design process are the process through which the product is made, so if the process does not accomplish the requirements it will definitely impact the product, which will definitely not perform as efficiently as it is required to in the design requirements or goals.

2.3.2.1 Building design process complexity

The following subsections will introduce the idea of the design process, specifically the building design process, which consists of a number of design stages. In addition, this section of the research will review the studies that have been conducted in the literature on building design process complexity.

2.3.2.1.1 Building design process stages

The product design process incorporates a number of stages that are organised in a specific order for designers and engineers to follow in order to demonstrate and illustrate the target of the product design and satisfies the functional requirements in the form of a designed product. This process consists of a number of steps designers use as a guide to follow in order to achieve the final outcomes of the product. These design processes are in the form of stages that consist of a list of descriptive tasks for each design team member involved in the design process of a project. Design team members have to execute the tasks required in order for the design process to move forward towards the accomplishment of the final product. Baher Ismail Farahat (2012) explained that planning and designing a product occurs as a process, which means they follow a sequence of actions and events that has to be formulated in the design process model to achieve the optimal design solution. Moreover, this process involves several multidisciplinary experts, such as lead designer, architects, construction engineers, civil and structural engineers, and health and safety engineers.

The building design process has a similar product design process, as we explained and urged in the next section that a building is a product. It is a series of actions that are undertaken by the building design team with the aim of establishing a building design.

The building design process consists of several stages; each stage has a list of design tasks assigned to it, and these tasks are required to be established in the design stage in order to establish the design stage outcome, which will be carried out to the next stages to establish their outcomes. This process continues to improve till the final stage of the building design process, which will establish the final design of the building. In this research, we will present a building design process model that consists of five design stages, which are defining the building stage, generating the solutions stage, concept design stage, developed design stage, and technical design stage.

The design process consists of several stages; each stage consists of several design tasks. According to the Oxford Dictionary, a task is "A piece of work to be done or undertaken". This definition indicates that it means a piece of work needs to be accomplished by specific person or application. This section introduces a prototype for the building design process that indicates the categories of tasks in each stage of the design process. These stages involve a series of activities that are carried out in a form of process. Each stage of the design process consists of requirements that need to be accomplished in order to continue to the next stage. The prototype of the building design process consists of five categories of design tasks that are required to be accomplished in each stage of the design process, as shown in Fig. 2.3. The categories of the design tasks that are built into each of the building design process stages are explained in the following paragraph.

First, identifying the requirements of the design process stage: each design stage has several requirements that the designers have to identify and understand in order to generate a solution that meets the requirements of the stage. Second, after understanding and identifying the requirements of the design process stage, the designers are required to set up multiple solutions that address those requirements. There solutions either a defining solutions or solving a design problem, or forming a design, etc. Third, evaluating the solution is a very challenging task due to the need to identify the optimal solution that meets those requirements of the stage. This task requires several methods to test the solution and measure how successfully it meets the requirements. Fourth, establishing the task relates to developing the optimal solution to meet the stage's requirements. Fifth, implementation of the design solution: this design task requires the final solution of the stage's requirements to be applied. In this task, the design team is required to finalise the accomplishment of the stage, which will be taken to the next stage of the design process.

In the following description the research will present the building design process stages, which are: defining the building stage, generating solutions stage, concept design stage, devolved design stage, and technical design stage, as well as the description of each task in the stage of the process. In addition, it will highlight the integration of the five required tasks in each stage.

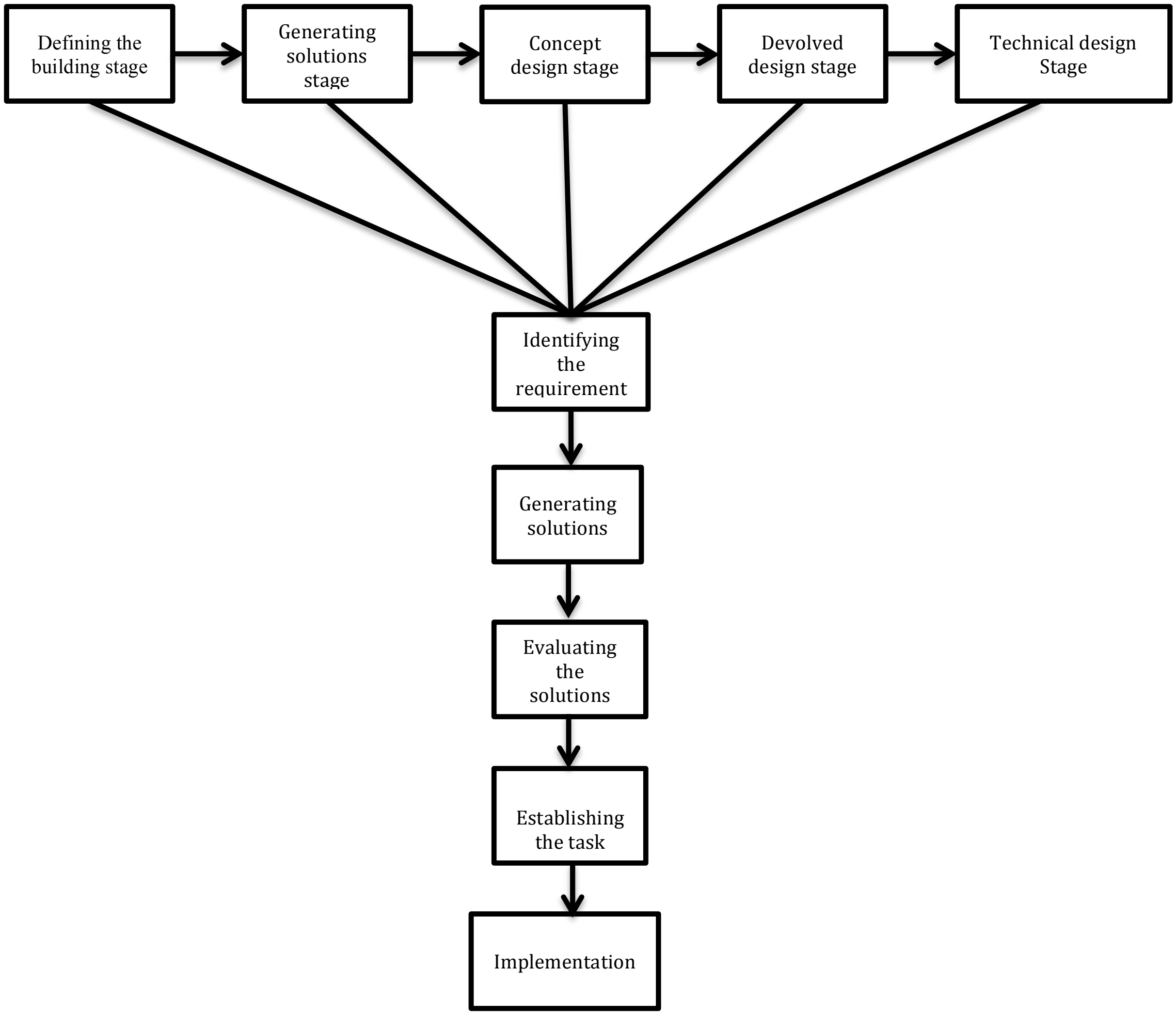


Fig. 2.3 Prototype of building design process stages

2.3.2.1.1.1 Building definitions stage

According to Johnson (2010), the product definition stage consists of recognising and clarifying the requirements for a product, which is followed by determining the specifications of the product that will be designed. However, Pullman and Keyson (2008) divided defining the project stage into three tasks, which are the functional statement, analysis, criteria and synthesis. The functional statement is the description of the design problem in the form of text. The analysis tasks form the stage of understanding the design problem and formulating it into a brief description from the designer's point of view. The criteria tasks are listing the targets that the design has to accomplish. Synthesis is a description of how the designers will achieve these targets. Moreover, the product definition stage can be split into two main tasks, which are defining the problem and gathering the pertinent information (Khandani 2005). First of all, "defining the problem", which starts with a clear definition of the problem by identifying what it is needed for. After defining this need, there has to be a clear problem statement to explain how the design problem will be solved. Then the design criteria need to be determining, in order to achieve the optimal design, which usually consists of a list of satisfactions that the product design has to meet. Next is "gathering pertinent information", which is collecting all the information that is related to the design problem as well as looking at the designer's solutions to similar problems. In order to gather specific information that is related to the design problem, the design needs to ask questions concerning whether the design problem needs new solutions, and if there are already solutions to it.

In this stage of the building design process, there are several requirements that this prototype identifies and describes. First, identifying the requirements of the design stage:

the requirements of this stage are encapsulated in a process that consists of three tasks: establishing the building design requirements, building goals and building specifications. Second, generating multiple solutions: the building design solutions of this stage consist of a list of various requirements, goals and specifications that the building is required to meet. Third, evaluating the solutions: after generating multiple design solutions for the building to the requirements, goals and specifications of the building design, the designers are required to evaluate the outcomes and determine the optimal specifications, requirements and goals that satisfy the building's needs. Fourth, one statement needs to be established by making a decision about which requirements, goals and specifications of the product are optimal for the next stage. Finally, the requirement of this stage has to be implemented by finalising the specifications, requirements and goals of the building in a form of text and description that includes each aspect of the building, what it accomplishes and how it will be designed.

2.3.2.1.1.2 Generating solutions stage

According Johnson (2010) generating multiple solutions for a product is a task that follows the definitions of the product specification. For this task, the designer tends to generate primitive solutions in a way that explains how the design meets the specification. In addition, Pullman and Keyson (2008) mention that in this stage of the design designers generate an external representation of the product design by sketches, drawings and models that meet the design specification as well as providing a simulation of the expected performance of the product. This means that while designers are generating the form of a product they look intensively at how this product will perform the function that is required in the specifications, which is considered as a significant aspect of the next task of this stage of the design, which is choosing the optimal solution. This was described in Khandani's (2005) model as two tasks, which are generating multiple solutions and analysing and selecting a solution. Gathering multiple solutions is described as proposing several solutions that tend to satisfy the design problem, which can be supported by looking at precedents of how designers have tended to generate solutions to a similar design problem as well as looking at the tools and applications that are used to generate design solutions. After this task, there is a need to analyse and select the optimal solution, which involves intensive investigation of each proposed design solution and evaluation of its predicated performance to make the right decision regarding which solution will be the optimal design that will be involved in the next design stage.

In this stage of the building design process, the requirements include generating multiple design solutions to the building that meet the implemented description of the product definition stage. In addition, the optimal design solution that meets the implemented description of the previous stage must be chosen. Second, a multiple solution that meets the requirements and goals and specification has to be generated. Third, the solutions need to be evaluated by determining the optimal solution that meets the building's requirements. The concept design of the building that will be developed to the next stage needs to be established. Fifth, the final concept design has to be implemented in the form of text description and schematic drawings.

2.3.2.1.1.3 Concept design

According to Johnson (2010), the concept design stage consists of tasks that change the requirements and specifications to meet the concept design. In this stage, the design solution is determined and needs to be evaluated by its satisfaction to the design specifications, requirements and goals. This evaluation is described in Pullman and Keyson (2008) as the tasks of evaluating the expected properties of the design and the expected future performance and the function of the design, and evaluating how well the design performs in terms of its criteria and goals. In addition, in this stage designers make design decisions, either changing the specifications and requirements or changing the design to meet the specifications and requirements. Khandani (2005) described the product design concept stage as the implementation of the design, which is building the prototype of the product. This prototype has to be tested according to the requirements and specifications of the product design and to ensure that it achieves the goals.

In this stage of the building design process, the requirements include evaluating the concept design in terms of meeting the specifications, requirements and goals. In addition, the requirements can be changed if necessary, as well as the goals, specifications and concept design to meet the implementation of the building definition stage. Second, multiple solutions have to be generated to satisfy the requirements, goals and specifications of the building and the concept design. Third, the concept design has to be evaluated in terms of its functionality and other design criteria and goals. Fourth, the optimal solution that meets the building definition implementation needs to be established. Fifth, the final concept design has to be implemented in the form of drawings and description that meets the implementation of the building definition stage.

2.3.2.1.1.4 Developed design stage

In this stage of the building design process, designers are required to develop the schematic of the concept design in more detail. The task at this stage is to improve the drawings and the documents of the building to clarify the initial concept design's main components. According to Ostime (2013), the developed design consists of information about the proposed structural solution to the schematic design and information about the estimated cost of the product or the building. In addition, this stage will include the developed design of the form and the system components of the building.

This stage of the building design process requires the final implementation of the concept design to be developed into more detailed drawings and described properties. In addition, it is necessary to find solutions to the structural proprieties of the building and the design of its systems or functional components. Second, multiple solutions for the building's structure and the design of its systems and functional components have to be generated. Third, the structural and the systems design in terms of the project's requirements, specifications, and goals have to be evaluated. Fourth, it is necessary to establish a developed design description and drawings including the building's properties, functional components and systems, as well as detailing the involvement of the building in its context. Fifth, the building's developed designs have to be implemented in the form of several drawings as a final description that clearly shows the building's properties in its context, as well as how it will be structured and its systems and functional components. This implementation of the building's developed design does include a description that will enhance the efficiency of the next stage, which is the detailed design in terms of the methods of constructing the building.

2.3.2.1.1.5 Technical designs stage

In this stage of the building design process, the designers are required to develop the final drawings and documents on how the building will be constructed. According to Ostime

(2013), detailed drawings consist of clearly described documents on how the systems are going to be assembled. These are the technical drawings, which show how the building is going to be constructed. They illustrate the components of the building in terms of its layout and details, as well as the methods of producing the components and the assembly of the building.

In this stage of the building design process, the requirement is to produce a technical drawing of the building design, which includes the connections of the building systems, measurements of the components, type of materials, and the methods of constructing the components. Second, generating multiple solutions to the building assembly plan. Third, evaluating the building in terms of the design specification requirements and goals. Fourth, establishing the solutions to the building assembly plan. Fifth, implantation of the final technical design that contains all the detailed drawings and construction plans to be handed to the construction.

2.3.2.1.2. Complexity in the building design process

This section of the chapter will focus on the complexities that accrue in the building design process by highlighting the factors that increase the complexity of each class of the building design process complexity. The design process complexity can be classified into three complexities, which are the complexity of modelling the design process stages, complexity of establishing the design process components or outcomes, and the complexity of information flow and knowledge diffusion through the design process tasks, components, and design team members. The complexity of information flow and knowledge diffusion between design process aspects is determined by the amount of information that is required to flow between design team members through the establishment of design tasks and design components. The following section will describe the factors that increase the complexity of the three classifications of complexity in the design process, and will bring in the previous studies on complexity in information flow and knowledge diffusion in the building design process, which is the focused area of the three classifications of complexity in the building design process in this research.

2.3.2.1.2.1 Complexity of modelling the design process stages

There are several requirements for modelling the design process. They are significant in achieving the optimal solution of the product function (Baher Ismail Farahat 2012). Modelling the design process has several requirements mainly: it has to follow a logical sequence that leads the stakeholder to achieve the goal of the building design. This indicates that designing a model of the process is a significant aspect that drives the building design to satisfy its requirements. In addition, O'Donovan (2003) determines certain criteria for modelling the design process, which have to identify the requirements for modelling as being appropriate and reasonable for a wide range of multi-discipline agents such as engineers, designers, operational management, strategic management, and academia. These requirements consist of four criteria aiming to enhance the efficiency of modelling the design process, which definitely result in enhancing the efficiency of the outcomes of the process as well as its performance. These requirements are scalability, practicality, maintainability, and robustness. Scalability of modelling the design process plays the role of involving appropriate stakeholders from multi-disciplines in the model. The need for scalability in modelling the design process is due to the variety of buildings in the field of design as well as the variety of complexity of the building components; some buildings are simple, others are complex. Therefore, the use of scalability in the design process is a significant aspect of modelling which can be illustrated and demonstrated in hierarchical groups of tasks in the design process model. Second, model practicality is a significant aspect of the engineering design process, which means that the design process model has to be designed so that the project's stakeholders can understand its elements and can function without the direct support of the researchers. The third criterion relates to model maintainability of the design process, which means that the model has functions as a dynamic system, so it has to have the ability to update its tasks and elements simply with the minimum amount of effort. The fourth criterion concerns model robustness of the design process, which requires constructing the design process model of a building in similar design process precedents rather than models that represent a variety of building design processes. This indicates the ability to identify the robustness of the design process model.

The previous requirement will be the driving tool in modelling the building design process. The design process model needs to be constructed in a hierarchical grouping of stages, which supports the ability of stakeholders to accomplish their tasks. Moreover, the model needs to be understood by several project stakeholders. The ability of a model's tasks to change during the design process is addressed to achieve its maintainability. The model will be built in a similar design process precedent, which can support the accomplishment of robustness in the model.

The previous criteria of the engineering design process drive the complexity in the earlier stages of the design process. The four criteria classify the complexity in the stage of designing the process model for the building and engineering design process. First, according to Pektaş (2006), there is difficulty in designing a hierarchal model, depending on the amount of tasks required. In addition, the complexity happens in two dimensions of designing the process the process sequence design with reducing the iteration cycle. Second, (O'Donovan 2003) relaying on a theoretical framework, in design process model the different discipliner involving in the process uses a different types of models there therefore, the complexity occur in designing the model to remain flexible and able to extend after its built. Third, (O'Donovan 2003) complexity of achieving the ability of design process model to become capable to updated simply with less time and effort from the users. The ability of the model to be updated relies on the use of technology that reduces the amount of time and effort to make changes to the design process. In addition, according to Krygiel (2008), building information modelling (BIM) is an example of a model that contains all the information for a building. And all the information is set up in a, therefore, and changes that happens in an object.

2.3.2.1.2.2 Complexity of establishing the design process components or outcomes

According to Ralph's (2009) design model, a design consists of several components that need to be dealt with in a specific process in order to achieve the final outcomes of the design, such as a building design. This section will review the factors that increase complexity in six significant design process components, which are the complexity of establishing a design problem, design specifications, design context, design goals, design requirements, designer and constraints.

2.3.2.1.2.2.1 Design problem complexity

According to Ulrich (2011), a design problem is defined in architectural design as the programming in building design; it is the interpretation of the customer's needs, which establishes the design solution. Defining a building design problem is a process of articulating what the designer aims to accomplish in designing the building. Basically, there are two targets that designers aim to establish in defining a building design problem, which are establishing the function of the building design and reaching the quality of building performing the function. In addition, Alexiou (2009) determined the factors that increase the complexity of defining a design problem. First, there is the actual procedure or a process of defining a design problem. Second, there is no right answer to the design problem solution due to the lack of method to evaluate the design solution; design solutions are good or better but there are not a perfect solution.

2.3.2.1.2.2.2 Design specifications complexity

Design specifications are defined as providing a "detailed description of an object in terms of its structure, namely the components used (out of the set of possible *types* of primitives) and their connections" (Ralph 2009). The design specifications consist of clear descriptions of the components of the object, product, or building. This description defines the components of the design and how they are connected to each other. However, Rodgers (2011) defined design specifications as a document that contains all the information that is required to produce the product. In addition, this study indicates the method in how to construct a design specification, which is by listing a problem that the design of the building, for example, has to meet in order to satisfy its requirements. Constructing building design specifications requires intensive research activity to define the building precisely.

As a result, the factors that increase the complexity in establishing the design specification of a building are in two dimensions. First, the complexity of excluding and including information that is relevant to the building in the research process. Second, the complexity of dealing with a large amount of information that needs to be organised in a specific order to move them forward to the next design team member to use in establishing other design process components.

2.3.2.1.2.2.3 Design context complexity

The environment of the product has been described as “the context or scenario in which the object is intended to exist or operate” (Ralph 2009). This context such, as the building’s context, is a significant component that influences the design process because it may be necessary to adapt the building’s context. In addition, there is a large amount of information related to the context of the design, such as the building’s context (Alexiou 2009). The challenging aspects are to categorise this information in order to solve its complexity and to determine the information that is needed for the building design. Moreover, Alexiou (2009) categorised the information as constant information, which is what designers can recognise, unknown information, which forms a challenge to achieving them, unnecessary information, which is information that exists in the building context, but is not needed for the process of designing the building, and unclear information, which requires clarification.

As a result, the complexity in describing the context or environment of a building is driven by the ability to determine the information that is needed for the building’s design from the building’s context.

2.3.2.1.2.2.4 Complexity of design requirements

There is a need to classify the building requirements in order to understand the relationship between them, which drives the wheel to analyse the complexity in building design requirements. According to Ralph (2009), “A requirement is a structural or behavioural property that a design object must possess”. This classification determines the building requirements as the list of satisfactions that a design solution needs to achieve. These requirements are divided into structural and behavioural ones; however, this does not include a very significant aspect of the building design requirements, which is the stakeholders’ requirements, which definitely enhance the efficiency of a building in terms of satisfying its needs and function.

The building design requirements have to be divided into two main classes, which are building design requirements, and the users required for reaching the satisfaction of the building use. First, the requirements of a building design are divided into two main categories. The first category describes the building’s condition in the environment, which means its structure, and how the building needs to be placed in its environment. These requirements consider the need for the building to be constructed, and determine the next requirement, which is the building performance requirements, and are influenced by any changes in it. These requirements describe the building performance that needs to be accomplished to satisfy its function. These requirements consider the need for the product to achieve its goals. The second category is the building users’ requirements, which are the services that are required for each user to gain specific satisfaction from the building design. These categories of building design requirements increase the design efficiency through the avoidance of conflict between building design and users’ needs.

In establishing the building design requirements, designers need to address several challenges during the design process. These challenges are the driving wheel to complexity in the establishment of building design requirements. The factors that cause complexity in terms of design requirements are categorised into two main complexities. First, determining the structure of components of the building that satisfy the required building performance. Second, determining specific needs for each user of the building as well as confirming their ability to compromise in the building. This relies on the ability to determine the qualification required for each user's needs in the design of the building and what qualification is needed for each building design problem.

2.3.2.1.2.2.5 Design goals complexity

Buildings goals are a description of targets to be accomplished in the form of a statement. This statement contains a certain level of ambiguity in terms of the methods or the way of achieving it. In addition, Ralph (2009) defined product goals as "what the design object should achieve", and argued that, as a building is designed and built in an environment, its targets have to be related to its environment. However, the goals of a building's design have to aim at more than building adaptation into its environment; the building has to achieve user, budget, and quality satisfactions.

Buildings goals have to be reflected in building performance. These goals influence each other in a challenging way. For instance, the building has to accomplish a specific performance, which indicates that there is a need for specific, high-cost components, which increases the building cost against the assigned building budget, so this increases conflict in building goals, which then increases the complexity in achieving the balance between building goals. These increases of complexity occur when goals of the building performance, for example, encounter other building satisfaction, such as building resources, quality and budget. In addition, the complexity of designing the goals of a building can increase when there is no method to measure the achievement of the building design goals. Linton's (2000) article described factors in measuring design goals, such as performance, cost, and quality. Balancing these factors in building goals can enhance efficiency in achieving the optimal solution to a building design problem whilst reducing the resources used. For instance, the speed of operating that is required in manufacturing building components or constructing building components can be accomplished when combining more than one function in a single component, which will decrease the manufacturing time.

As a result, there are three main factors of complexity in designing the goals of a building. First, the ability to satisfy the goal factors in a balanced idea. This complexity increases when the building has to accomplish an environmental adaptation, users' satisfaction, and high quality with as low a cost as possible. Second, determining a method to measure the satisfaction of the goals' achievement.

2.3.2.1.2.2.6 Design boundaries complexity

Designs boundaries are constraints that determine a building's properties in terms of its structure and performance. They are an efficient statement that significantly enhances the design process by knowing the building's function and performance restrictions, which works as a guide for the designers. Moreover, the design boundaries challenge the creativity of generating the building design.

Ralph (2009) defined the design constraints as structural and behavioural restrictions of the design as well as comparing them to requirements of the designed product. However, the building design boundaries are not exactly similar to the building requirements, because the requirements are related to the achievement of the functions and goals of the design, whilst the boundaries are related to unsatisfactory functions and performance of the building. Therefore, this section will classify the restrictions of the building design into two main boundaries. First, specification boundaries, which are clear restrictions relating to whether a building or its components meet the structural properties required in the design specifications. Second, building performance boundaries, which means a building, a part of it, or a component do not perform or function according to the building goals.

Two factors increase the complexity of determining the building design boundaries. First, complexity that occurs when the number of restrictions increases, which necessitates the ability to generate multiple design solutions and enhances creativity. Second, the complexity increases when the design solution satisfies the goals of a building's performance and conflicts with the design boundaries, which increases the amount of testing for a building concept's design.

2.3.2.1.2.3 Complexity of information flow and knowledge diffusion in the building design process

This section of the research will present very significant aspects of complexity in the building design process, which are the complexity of information flow and the knowledge diffusion through certain aspects of the building design process: the building design process's components or outcomes, the building design tasks, and the building design team members.

2.3.2.1.2.3.1 Complexity of information flow in the building design process

The information flow in the building designs process is not a simple path that can be modelled; moreover, it takes place between the three aspects of the building design process. In addition, Eckert (2001) described information flow in the design process as chaotic and unpredictable. Including that tracking information flow through the design process for the propose of guiding the design outcomes is not necessary; however, what is significant is recognising what information experts need in order to model the flow of information through the design process. In addition, Austin (1999) modelled the design process information flow by identifying the information needed in each task of the design process, which helps to identify the progress of programing the design in accordance with the design process.

This prototype model classifies the information in the design process task into external information and internal information. External information is information that is received from an external information source in order to accomplish a specific design task, whilst internal information is information that is received from the outcomes of a design task in order to proceed with another design task. The complexities of modelling the flows of information between designs tasks are indicated in determining the information that is needed for each design task and the ability to determine the information flow paths between design team. Therefore, the increasing complexity of information flow in the design process is split into three four significant factors: the complexity of information interactions, information dependency, and information exchange and communication through design agents.

2.3.2.1.2.3.1.1 Complexity of task interactions

Interactions are actions that happen when two or more components of a system have an effect on each other. In the design process, interaction is determined by the information flows from the design tasks to the design team member who establishes the design task to become and the design process outcome or component. In addition, the interactions between design tasks can significantly be described as the impact of accomplishing a specific task on another task. Each design task has an impact that influences a change in another design task or helps to accomplish another design task. Studying the impact of a design task needs to be determined by the ability to model the connectivity between tasks and determine which design task can be influenced by a change in another design task. In addition, Eckert (2009) designed a process model that needs to involve the investigation of the effort that needs to be accomplished in the design task in order to avoided iteration and delay in the design process. Therefore, modelling the impact of each design process task on another is a significant aspect that can determine the most influential task that causes iteration and delay in the design process. In addition, the more interacted the design process task, the greater its effect on the whole design process. This effect drives the complexity factors when the number of design task interactions increases the possibility of delay and iteration occurring in the product design process. Investigating the interactions between design tasks in terms of the most interacted and influential tasks can significantly increase the prediction of change in the design process due to one change that can happen in one design task or more.

2.3.2.1.2.3.1.2 Complexity of information dependency

Dependency between design tasks is a very significant aspect that increases the complexity of accomplishing the design tasks. Dependency between design tasks means that one task cannot begin or end unless another task is accomplished or has started. There are several types of dependency between the tasks in the design process. According to Jessop (n/d), there are four types of dependency in design tasks, which are finish-to-start, finish-to-finish, start-to-start, and start to finish dependency. Finish-to-start dependency means that a design task cannot be started until another task is finished. Finish-to-finish dependency means a task cannot be accomplished until another task is accomplished. Start-to-start dependency means a task cannot be started until another task is started. Start-to-finish dependency means a task cannot be accomplished until another task has started. These types of dependency between tasks indicate the significance of modelling the dependency between design processes in order to enhance the efficiency of the design process. Modelling the dependency of design tasks is significant due to the need for design process time management. In addition, the more dependent a design task, the more influential it is in the whole design process due to its impact on other tasks.

2.3.2.1.2.3.1.3 Information exchange and communication through design agents

The design process involves a lot of agents that work as a team to finish the building or accomplish the outcomes of the process. This team of agents varies in terms of experience and educational background as well as the tasks that each team member is assigned in the design process. These design agents require significant methods of communication that ensure the efficiency of the design outcomes. There are several factors that increase the complexity of communication between design agents during the design process. According to Whyte (1996), the difficulty of communication that accrues between design team members from different disciplines increases the complexity of the design process. In addition, Eckert (2001) stated that the complexity of communication between members of a design team accrues due to the inability to balance two activities, which are how individuals exchange information in a specific interaction, and how a large amount of information is organised. Balancing those two factors decreases the complexity of the design process. Moreover, the study added more factors that increase the complexity of communication in the design process, such as team members not being able to understand the big picture of a complex product design, which can cause the design team to lack understanding of the design task, its information, how this information can be applied in the design, and changes that can happen in the design process.

2.3.2.1.2.3.2 Complexity of knowledge diffusion through aspects of the building design process

The diffusion of knowledge has been defined "as the movement of the useful ideas between organizations" (Appleyard 1999). There are several technologies that enhance the diffusion of knowledge between the agents of a system or an organisation, and the distance between the components varies depending on the type of technology used. According to Canals (2005), knowledge diffusion through a network takes place via two processes. First, is the formal interaction: this interaction happens face to face or in a meeting or through using technology such as emails or videoconference; this type of knowledge is intended by the organisation. The second type of knowledge diffusion is usually through the social relationships of an employee in the firm or a network of practice; this type of knowledge diffusion is considered intended knowledge diffusion.

This research will focus on modelling knowledge diffusion in the building design process through the three main aspects of the building design process, which are design, tasks, design team members, and design process components. The following studies have contributed to the field of modelling knowledge diffusion in the building design process. First, in the paper *"Modelling and managing project complexity"* (Austin 2002), the study brings the four stages of the building design process to the analysis of the information flow and diffusion of knowledge. In addition, the research has established a detailed model of the concept design stage as a framework for the information required to flow in order to achieve the outcome of the design process. The modelling of the information flow is shown in Fig. 2.4 of the concept design stage. The model consists of design tasks that the design team are required to establish in the concept design process stage. The model divides the design tasks into tasks that are related to the business needs and to the design strategies, and indicates the two most significant tasks that are repeated from the client for both business needs and design strategies. In addition, the research presented a way of modelling the design tasks, which is through a dependency structure matrix, as shown in Fig. 2.5. The matrix lists tasks in the rows in alphabetical order and the order is mirrored in the columns of the matrix. Then the matrix presents a dependency, which means an informational interaction between two tasks in the interaction between the column and the rows. This dependency is presented in a scale of A, B and C, which indicates the strength of the dependency between the tasks' information. This matrix models the information interaction between the design tasks in order to reduce the iteration and determine the optimal sequence of the building design process's tasks. As shown in Fig. 2.5, the number of critical marks above the diagonal line in the matrix is reduced as the iteration in the process, which is shown as the shaded blocks. This tool for modelling the interactions between the design process tasks gives the building design team members a clear vision of the exact time the information is needed in the design process, and the ability to update information in the design accurately, which helps to manage the risk, estimate cost, and, more importantly, it helps to ensure the information is exchanged appropriately and accurately between the design team members. This can be analysed by investigating the controllability of the design team members in diffusion of knowledge in the building design process. The use of the design structure matrix improves the analysis of knowledge diffusion in the building design process aspect by modelling the interactions of them using this method.

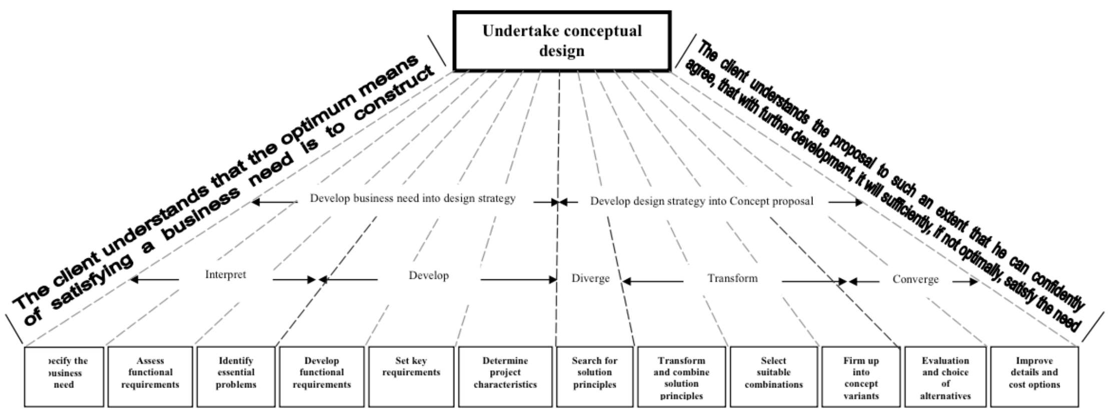


Fig.2.4 Conceptual design framework based on Austin (2002)

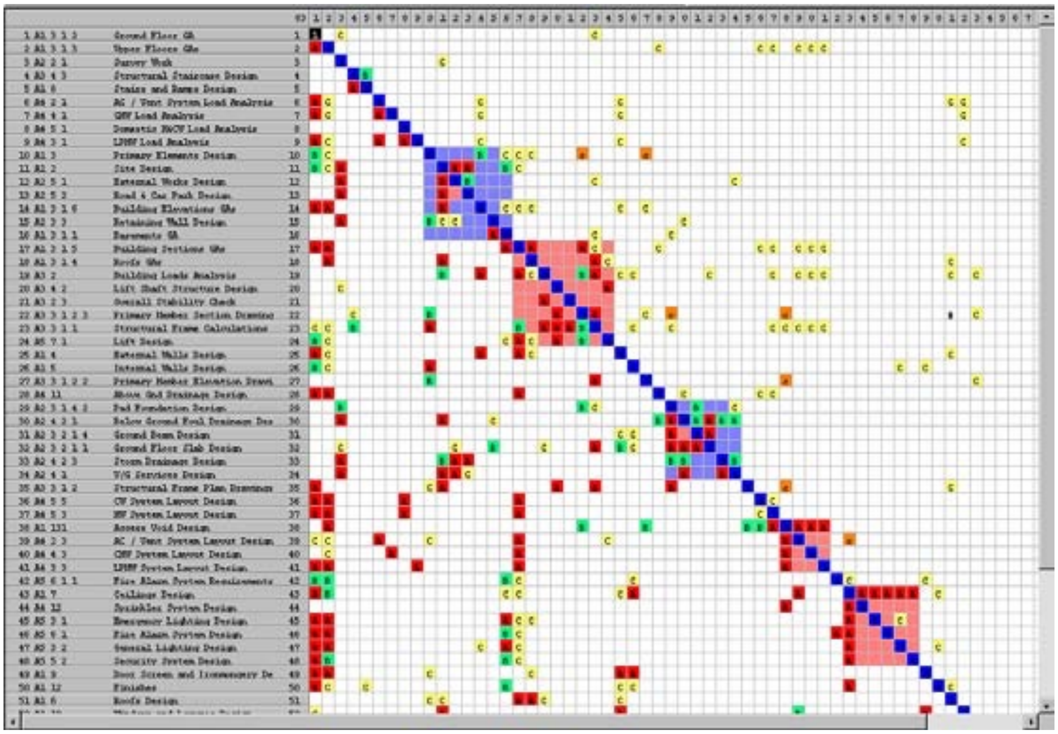


Fig. 2.5 Dependency structure matrix based on Austin (2002)

2.3.2.2 Complexity of building systems design

The following section will introduce building systems design as well as indicating the factors that are increasing its complexity. In addition, this section will review the literature on complexity in building systems design and indicate the factors that are significantly important in designing building systems that are more resilient to the phenomena that they are designed to resist.

2.3.2.2.1 Building systems

Buildings consist of a large number of components that interact with each other to form the building systems. The building systems are all the engineered systems in the building. Building systems include “architectural, mechanical, electrical, and control systems along with their respective subsystems, equipment, and components, all of which must be commissioned". Each of those building systems consists of a large number of components that make the system stand for the function for which is has been designed. The building systems that will be analysed and investigated in terms of their design resilience to changes and failure of components are the architectural design, structural design, envelope design, mechanical design, electrical design, and lighting design. Those systems are considered to be complex systems because they are characterised by the complexity systems' definitions in the literature, such as "A system whose behaviour exhibits complexity"(Johnson 2009). This definition supports the idea of complexity in the building system's performance. In addition, in terms of the interactions of the building system and its components, Simon (1962) describes it as: "One made up of a large number of parts that interact in a non simple way"; this indicates that a complex system contains a large number of components interacting in a very complex way, which is indicated in the design of the building's systems, such as architectural circulation, structural components, envelope system, etc. Moreover, those complex systems' components are not able to function by themselves; they have to interact, to work together in order to achieve the function for which they were designed. This is indicated in the following definition of a complex system: "A set of different elements so connected or related as to perform a unique function not performable by the elements alone"(Maier 2000).

In addition to the previous argument that building systems are complex systems that can be designed using the approaches for designing complex systems as well as can be analysed and assessed from a complexity science point of view, buildings systems need to be designed with consideration of the resilience stages of their design. In other words, building systems have to be resilient to several phenomena that are interacting and affecting the building design. Those phenomena vary and designers have to take them into consideration while designing the layout of a building. The following subsections indicate the factors that are required to be taken into consideration when designing a building system, which are architectural systems, structural systems, envelope systems, HVAC system, power systems, and lighting systems.

2.3.2.2.1.1 Building systems resilient design

According to the Oxford Dictionary (2014), resilience is defined as "*the ability of a substance or object to spring back into shape*" and "*the capacity to recover quickly from difficulties*". These definitions indicate that a system can be resilient when it has the ability to recover from changes that occur in some of its parts, such as an external effect of one or more of its components. According to the Resilient Design Institute (2015), resilience is "*the capacity to adapt to changing conditions and to maintain or regain functionality and vitality in the face of stress or disturbance. It is the capacity to bounce back after a disturbance or interruption*". In addition, the Resilient Design Institute (2015) defines resilient design as "*the intentional design of buildings, landscapes, communities, and regions in response to these vulnerabilities*". The vulnerabilities that are meant in the above definition are the ability to maintain in a condition of natural disaster, loss of electricity, climate change, storms, flooding, etc. This research will highlight the vulnerabilities that can happen to each system in a building and indicate how resilient buildings are to them.

2.3.2.2.1.1.1 Resilience in a building's architectural system

One of the significant aspects of designing the architectural system of a building is the design of the circulation flow in the building. This refers to the paths that people move through to interact with the building. According to Puusepp (2011), the circulation design of a building provides access to the building environment, such as spaces. An entrance that is linked to a corridor, which is an element of the building circulation design, provides access to an architectural space. A good circulation design requires several criteria to be fulfilled, which are (Puusepp 2011): the circulation flow has to provide the goal required to access spaces in the building, and the circulation space has to be designed to optimise the length of the circulation corridors to connect spaces that are required to be close to each other. However, this research is focusing on a significant aspect in assessing the building's architectural design, which is the design of a circulation that is resilient to fire and which enhances the efficiency of the circulation flow in case of fire.

There are several studies and tools that are significant in designing the architectural layout to be accessible to fire escape. According to LWF (2015), there are significant questions to ask in terms of fire escape assessment when designing the building layout. Those questions are: "How do I know if building users can escape safely?" "How many people can escape from one fire exit?" and "Where can fire exits be located?". These questions can be answered using several parameters as a tool to ensure a good level of safety when designing the building layout. The study indicates several factors that have to be taken into consideration when designing the layout: the "number of occupants", "the number of escape routes", "width of escape routes", and "computer models".

First, the number of occupants: designers need to determine the number of users who will be in the building. The study presents two methods of calculating the number of occupants in the building, which are determining the floor space using 6m per person in the building and determining the capacity of the escape routes in order to determine the number of occupants.

Second, number of escape routes: when the number of occupants in the building is determined, the number of escape routes has to be enough for all building users to escape. The study presents a quantifying table below that recommends the number of escape routes necessary relevant to the number of occupants in the building.

Table 2.1 Recommended use of escape routes per floor in relation to the number of occupants LWF (2015).

Maximum number of people	Maximum number of people
60	1
600	2
More then 600	3

Third, travel distance, which is the distance between the person and the fire exits. In the study, the travel distances vary from one building type to another; however, in office buildings the travel distance has to be 15m if the exit is in one direction, and 5m in two directions.

Fourth, the number of occupants in the floor can determine the width of escape routes: as the number increases, the width of the floor has to increase.

The research used a computer model to assess the specific escape routes in the building.

This computer model requires certain inputs, which are the previous factors of number of occupants, location of fire escapes, and the length and width of the fire escapes. Then the model shows a simulation for the time it takes to evacuate the building, and it can also indicate the evacuation of a specific space in the building. Fig. 2.6 indicates the factors that have to be taken into consideration when designing circulation spaces in a building to be resilient to a fire.

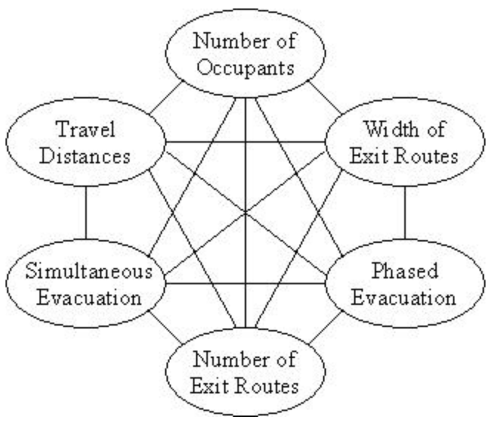


Fig. 2.6 Interactions of design factors in a successful circulation space in terms of fire exits

2.3.2.2.1.1.2 Resilience of a building's structural system

The structural design of the building is the design of the skeleton holding the building components and making it stands against outside effects and impacts. The design of a building's structural system of transfers the loads of the building's weight through its components. There are several types of structural system used in buildings, depending on the function of the specific building. The study classified the structural systems of tall buildings into three classifications, which are steel buildings, reinforced concrete buildings, and composite buildings, and indicated the variety of each structural system.

According to Gunel (2007), the most significant aspects in designing tall buildings are its resistance to wind and earthquakes, which increases the ability to design higher buildings. Earthquakes are a significant phenomenon that affect the structure of a building and can cause significant damage to it. However, the improvements in technology and building materials have enhanced the robustness of buildings' structural systems and their resilience to this phenomenon. Several tools and studies have been established to assess a building's structural system resilience to earthquake damages. Although there is no building structural system design that can withstand all earthquake damages, the design of structural systems has to withstand the largest earthquake that occurs in the location of the building. There are several methods that can assess the resilience of a building's structural system to earthquake damage. The most significant aspect used by designers when designing the structural systems to be resistant to earthquake damage is base isolation.

There are several studies that assess the resilience of a building's structural design to earthquake damage. However, the focus in this research is on indicating the impact of damage to one structural component on the other structural components of a building.

2.3.2.2.1.1.3 Resilience of a building's envelope system

The envelope design of a building is a design of the façade of the building that separates the inside of the building from the outdoor spaces. The design of the envelope systems of the building protects the building from external effects such as wind, heat, etc. It also helps to provide aspects that are required from the outside, such as ventilation, natural lighting, etc. According to Ted J. and Kesik, B.(2015), the most significant aspects when designing the building envelope are its resilience to wind loads, controllability of the thermal flow, controllability of the airflow, moisture flow, sound transmission, and fire resistance. However, this research will study the impacts of those phenomena on the case study building architectural spaces, which can significantly enhance the ability to assess the building envelope design in terms of its resilience to these phenomena, more specifically, the design of the layout organisation according to the design of those needs for architectural spaces.

2.3.2.2.1.1.4 Resilience of a building's HVAC system

The HVAC system of a building is the design of the heating, ventilation, and air-conditioning, which is a technological design for controlling the environment of an indoor space. The design of the HVAC system of the buildings is aiming to provide a good quality of air and maintain thermal comfort of the spaces in the building. One of the significant aspects when designing the HVAC system of a building is the consideration air quality and the consideration of the air flow in the building and from one space to another. According to Lange (2005), certain areas of a building are susceptible to pollution, which affect large spaces in the building, which are mailrooms, shopping centres, and lobbies. This research will focus on studying the impact of air pollution in specific spaces in a building and assess how resilient the design of the HVAC system is to this phenomenon.

2.4 Conclusion

This chapter of the research has introduced complexity theory and the types of complex systems. In addition, it has introduced the complexity theory definitions and the characteristics of complexity of complex systems. Moreover, it has reviewed the literature on complex systems' principles, which are mainly characterised by self-organisation, diversity, history and time, unpredictability, and pattern recognition.

The chapter has also reviewed the complexity of design literature, which is the main aspect of this chapter of the research. The literature that was presented defines the complexity of design in architecture and the engineering; however, the most significant definition that determines the complexities of design is definition (Ameri 2008). In relation to architecture and engineering design, the complexity was analysed and measured in three main classifications, which are complexity of design problem, complexity of design process, and design product. As a result, the research has classified the complexity of building design into two main aspects, which are the complexity of the design process and the complexity of the design product. In addition, after reviewing the literature this chapter has introduced the factors that increase the complexity of the building design process and the building design product.

The complexity of the building design process is classified in this chapter into three min aspects, which are the complexity of modelling the design process stages, the complexity of establishing the design process components, and complexity of information flow and knowledge diffusion. The chapter has reviewed the factors that increase the complexity of each of the three main aspects of the building design process. In addition, the complexity of the building design product has been classified in this chapter into complexity of architectural design, structural design, envelope design, HVAC design, power design, and lighting design. The chapter has also reviewed the factors that increase the complexity of designing a building's systems to be resilient to changes.

CHAPTER 3: TOOLS FOR ANALYSING AND MODELLING COMPLEXITY IN DESIGN

3.1 Introduction

This chapter of the research will present the several tools and techniques that are used in the literature on analysing and modelling complexity in design. Those tools are used to significantly enhance the efficiency of understanding interactions among systems' components and indicate the significance of one component to another. In reviewing the literature from several studies analysing complexity in the design process and the complexity of the designed product, the research will determine the tool used in this research to model the complexity of the building design process and building system's design. The tools that are used in this research to model and analysis complexity of the building design process and product are the network modelling techniques and measures. The use of networks has significantly enhanced the ability to model and analyse the diffusion of knowledge specifically in the design process, as well as enhancing the ability to model and analyse complex systems such as the interactions of a building's components and indicating several analysis to it resilience to a certain design phenomenon.

3.2 Tools for modelling and analysing complexity in design

This section of the research will review several research techniques that model the complex design process, information flow and diffusion of knowledge into a form of models that simplify and reduce their complexity, which significantly enhances the efficiency of the design process. The tool used is the design structure matrix, according to (Browning 2015) the article raises very significant questions on managing the design process complexity: How do you get thousands of engineers to agree on the design of a product ? How do you design a product to be modular so that you can change a part of it and upgrade it? How to make sure that information flows in the design process between the team without an overload of information? The problems in these questions can be addressed by using the tool for managing and simplifying complexity, which is the design structure matrix. The design structure matrix is a tool that significantly helps model the complexity of a process and determine the pattern information flow between the design task and design team members. Moreover, the design structure matrix has been used in the field of modelling complex systems and helps to define patterns of the relationships between its elements.

According to Browning (2012), the design structure matrix is a matrix that is built in a square shape with elements of the components in the left and in the upper side of the matrix, and the cells between them, which are on a diagonal, represents the relations between those elements. As shown in Fig. 3.1, the matrix consists of six elements that have a direct relation or interactions; this can be dependency or a flow of information. The dots in the cells of the matrix represent the interactions between the elements of the matrix. For example, the dots on the first row indicate interactions between element 1 and element 2; this interaction can be an indication of information that flows from element 1 to element 2 or a dependency. Furthermore, this interaction can be taken in terms of modelling complexity of a process, which can indicate a relationship between establishing a design task to another, or a design task and the design team member who is required to establish it. On the other hand, this use of the design structure matrix indicates the relation between elements of a system or the design of a product, such as an interaction between one architectural space and another in designing the layout of a building.

In conclusion, the design structure matrix is a significant tool in modelling the complexity of design process information flow and knowledge diffusion. In addition, it is a significant tool in modelling the complexity of elements of a complex system in order to investigate the relations between the system's components for a better design solution. According to Browning (2012), the design responsibility matrix provides similar results to graph theory, which is going to be reviewed in the next section as a tool for modelling complexity of processes and products.

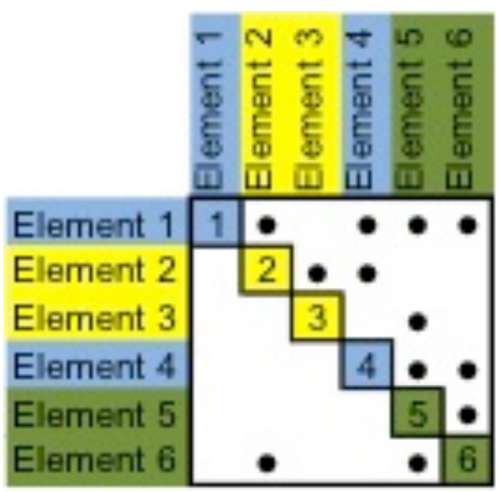


Fig. 3.1 Interactions between six elements using the design structure matrix tool Browning (2012)

3.2.1 Use of the design structure matrix in modelling the complexity of a design

Several researchers to model the complexity of the design process have used the design structure matrix. This section of the research will review several studies that have enhanced the method of modelling complexity of the design process using this matrix.

According to Pektaş (2006), building design has increased in complexity, which has forced professionals in the building design field to improve the tools that they use to model the building design process. However, the improvement that has been made in the field of construction is very significant in comparing the building design process. In addition, the study has defined the design process models into two types: the generic design process models and the formal activities of the process models. An example of a generic design process model is the RIBA plan of work. The generic design process models represent the design process in a form of design stages, with one stage after another. However, the formal design process models represent the activities of the design process in a form of network models, information flow models and design structure matrix models. Research (Pektaş 2006) has categorised the design structure matrix into two types, which are static and time-based design structure matrices. There are two types of static model, which are the component-based design structure matrix, which presents interactions between an existing system's components, and the team-based model, which models the interaction between design team members in a design process. In the time-based design structure matrix, the order of the rows and columns in the matrix represents a time sequence. There is the time-based activity design structure matrix, and the parameter-based design structure matrix.

Pektaş' (2006) study presented a case study of the design process for a suspended ceiling in a public building. Fig. 3.2 presents the design structure matrix of the case studies used in the research to model the design process dependency in terms of design process and system level.

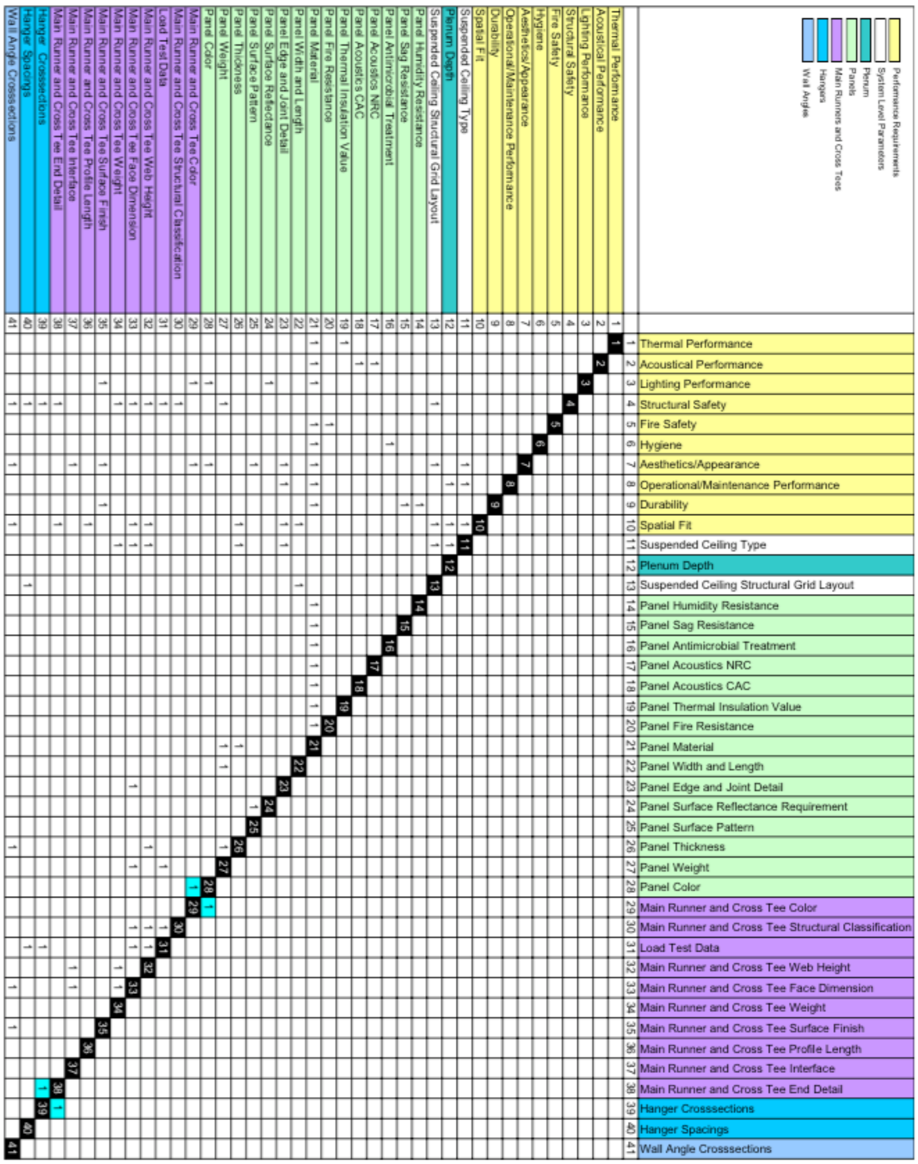


Fig. 3.2 Design structure matrix of the case studies used in Pektaş (2006)

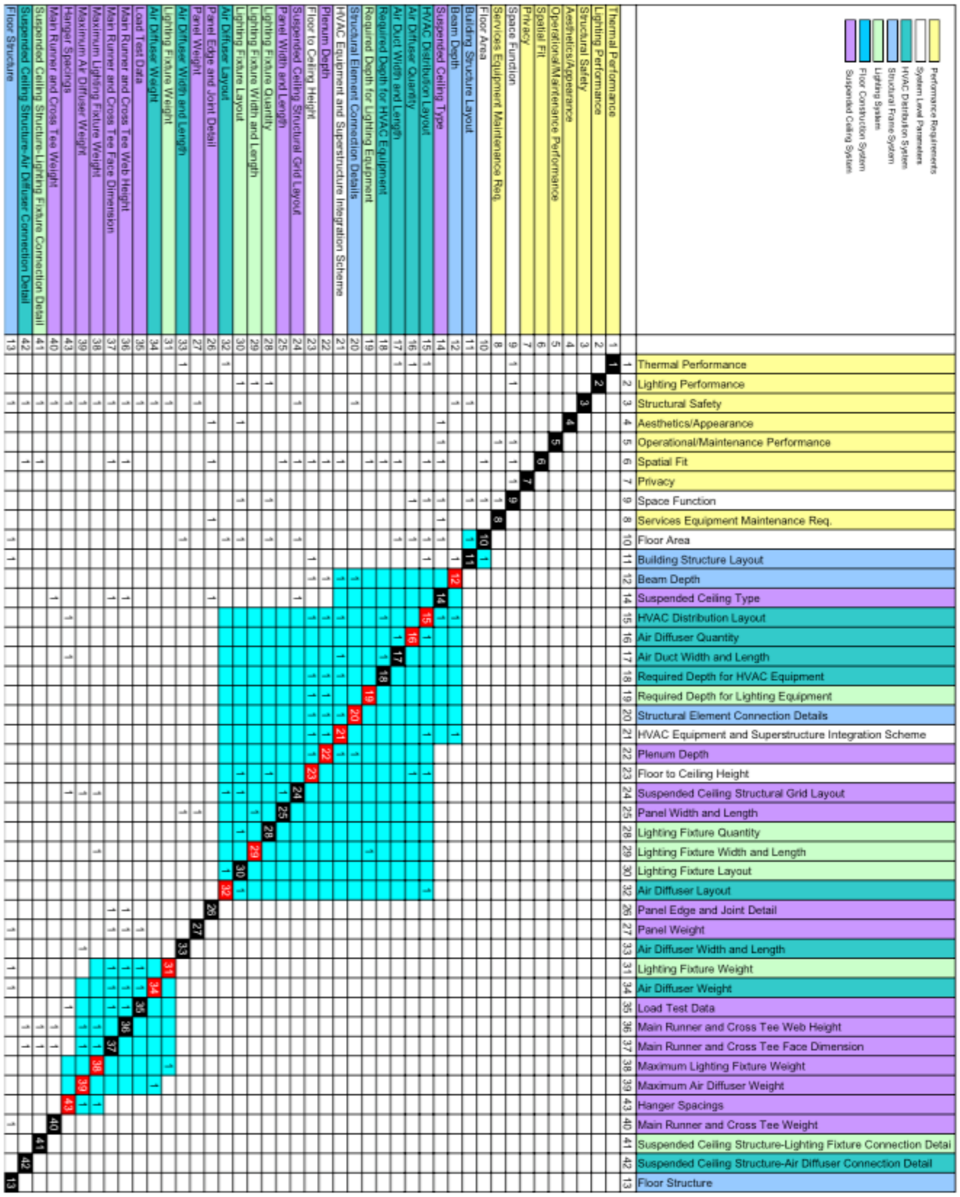


Fig. 3.3 Design structure matrix of the case studies used in Pektaş (2006)

The study presented an analysis of the results of the entries of both design structure matrices and compared the results of the assembly level and the system level components' interactions and indicated the variety of results for each design structure matrix. The interaction of the system's components resulted in 165 interaction points, which refer to information flow between the system's components; however, the interactions between the system's components in terms of the assembly dependency resulted in 97 interactions. This indicates that the system's ceiling interaction components are more complicated than the design process of assembling the ceiling.

In addition to the previous study using the design structure matrix to model the complexity of a design process, Yassine's (2004) research paper indicated that design of a product requires a large number of interactions between different professions in the background of the design team, which forms a complexity of design that needs to be modelled in an efficient way to enhance to outcomes of the resulting product design. In addition, the paper indicated that the design structure matrix is a significant tool to model the complexity of the design process in terms of information flow and dependency of the design information. The research defined the design structure matrix as a method of exchanging information that presents the design task and design team relations to determine the pattern of a sequence between them in groups. The research paper presented several uses of the design structure matrix in modelling the design process and indicated the interactions between the design requirements as well as the interactions between the system's components. The research presented the possibility of modelling the design process interaction among design team members when designing an automobile engine. In addition, it presented the possibility of modelling the engine in terms of components' interactions with a classification of the interactions between the system and the subsystem components' interactions. Table 3.1 indicates the possibilities of generating a design structure matrix of the interactions between system components of the automobile design.

Table 3.1 Possibilities for the design of a structure matrix that can be generated for interactions between system components of an automobile engine(Yassine 2004)

Interactions	Description of the design structure matrix of the system's components' interactions
Spatial interactions	"Identifies needs for adjacency between two elements. Associations of physical space and alignment" (Yassine 2004)
Energy interactions	"Identifies needs for energy exchange between two elements"(Yassine 2004)
Informational interactions	"Needs for data or signal exchange between two elements"(Yassine 2004)
Materials' interactions	"Needs for material exchange between two elements"(Yassine 2004)

Each of the following classifications of interactions can be modelled as a design structure matrix that generates significant results and analysis of the design of the product and can reduce the complexity of the system's design in terms of designing the product.

3.3 Tool for modelling and analysing the complexity of the design process (network modelling and analysis)

The desire to analyse the complex interactions of complex systems has led to a very significant science of networks. This science has increased our ability to understand complex systems in the natural world as well as to engineer complex systems. Using the network analysis methods has enhanced our ability to understand the complex interactions between complex systems' components as well as our ability to enhance the efficiency of the complex systems' design process modelling and performance. In this section, the research will concentrate on reviewing the literature on the network theory and measures. The outcomes of the research will be divided into two main sections: the first section will explore the network science and theories in the field of networks, and the second section will introduce the methods of analysing complex networks by identifying the significant measures used to uncover the complexity of complex systems. This section of the research will introduce the main categories of network analysis measures that will be applied in this research to uncover the complexity of the building design process and the complexity of designing a building product.

3.3.1 Network definitions

According to the Oxford Dictionary, a network is defined as “A group or system of interconnected people or things”. This definition indicates that a network is a system that consists of a large number of interacting components; these components are the system’s components and can be either people or things. As result, it indicates that the interactions between the system’s components can vary in terms of the connectivity methods, such as the people’s interactions are mostly information interactions; however, a thing’s components can be either informational interactions or a physical interactions, such as components of a complex system. In addition, Mitchell (2009) defined networks as a collection of nodes and links that connect the nodes to each other. The nodes represent an individual’s aspect of the network and the links connects those aspects together. In addition, Mitchell (2009) defined network thinking, which is what this research is using to investigate the complexity of the building design process and building systems design, as network thinking is a science used to investigate interactions and complexity in several disciplines. This use of network thinking and analysis has led to the determination of the common aspects and characteristics of different networks. Moreover, according to Mitchell (2009), network thinking is "focusing on the relations between entities rather than the entities themselves". This led the research to investigate the networks in two main approaches, which are the structure or the typology of the networks, and the attributes of the networks' components, which indicate measures that can be used to analyse the factors increasing complexity in the building design process and building systems' components.

3.3.2 Network science

Network science is a field that studies the complex networks of several disciplines, such as telecommunications networks, Internet networks, social networks, biological networks, and semantic networks. This field has several specific methods and theories for graphic theories, statistics, and information visualisations to study several phenomena in the field, which will help to predictive models of these phenomena (Press 2006). As a result, the network science is a science that analysis a complex system's interactions in order to predict the performance of this system in a certain phenomenon. In this research, the network science theories will be applied to investigate the complexity of the building design process, and building systems design in order to uncover the complexity that is driven by the factors that increase complexity in the phenomena of managing the building design process as well as the phenomena of designing the building systems.

3.3.3 Network theories

Network theory is part of graph theory and can be applied to several disciplines, such as computing, physics, engineering, and biology. Network theory investigates the complexity of the relationships among components in a graph. The application of network theory includes several kinds of networks, such as logistics networks, worldwide networks, the Internet, and social networks. As a result, using the network theory applications will significantly enhance the ability to model the relations between the aspects of the building design process, as well as the relations between the building layout design components.

3.3.4 Network analysis

Network analysis is defined as "Breaking down a complex project's data into its component parts (activities, events, durations, etc.), and plotting them to show their interdependencies and interrelationships". This definition indicates that network analysis is the process of breaking down complex interactions between a system's components and arranging them as data to import them into a network application that plots the data of a complex system into a graph that illustrates the interactions and relationships among the system components. In this research, the analysis is going to cover three areas of network analysis, which are the typological characteristics of networks, the analysis of knowledge diffusion in networks, and the analysis of the network components' resilience to certain design phenomena.

3.3.4.1 Network typological characteristics

According to Beal (2011), network typology refers to the layout of the network and how the nodes are connected to each other, and the communication among these nodes is determined and measured by the analysis of the network typology. There are two types of network typology, which are physical and logical. An example of the physical network typology is a device or system's connectivity between its components, and an example of the logical typology of a network is the communication between the social network nodes of the data signal from one device to another. The following subsections will define several types of network typology, which are mesh, star, ring, and tree typology.

3.3.4.1.1 Mesh typology

Mesh typology is a type of typology in which every node in the network is connected to every other node in the network. Fig. 3.4 shows an example of this type.

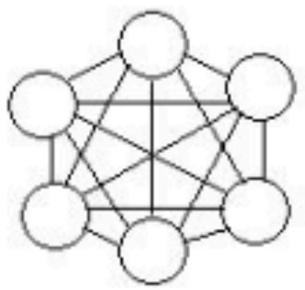


Fig. 3.4 Network mesh typology according to Beal (2011)

3.3.4.1.2 Star typology

Star typology is a network that consists of a central node that is connected to all nodes in the network and passes information through them. Fig. 3.5 shows an example of this type.

Fig. 3.5 Network star typology according to Beal (2011)

3.3.4.1.3 Ring typology

Ring typology is a network where all the nodes are connected in a closed loop. Fig. 3.6 shows an example of this type.

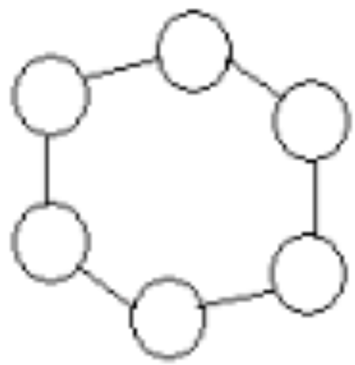


Fig. 3.6 Network ring typology according to Beal (2011)

3.3.4.1.4 Tree typology

The network tree typology is a group of star typologies that are connected to each other through the connectivity of central nodes, as shown in Fig. 3.7.

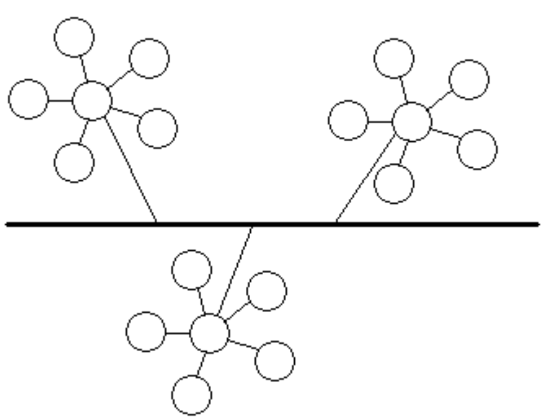


Fig. 3.7 Network tree typology according to Beal (2011)

3.3.5 Analysis of network typology in previous studies

This section of the research will review several studies that have used the network typological characteristics to uncover the complexity of interacting aspects, components, and factors of complex systems.

Research by Boussabaine (2010) presents the typological characteristics of a network that is built based on the data from a survey approach to the analysis of ecological building design fitness measures. The research constructed the network using the interactions between the ecological fitness measures of the ecological fitness measures the nodes presents the factors, and the edges of the network present the interactions between the factors. The research has used several network measures to analyse the typology that is built in Fig. 3.8. Those measures are the centrality measures, which are degree centrality, closeness centrality, and betweenness centrality, which are indicated in the results table in Fig. 3.9.

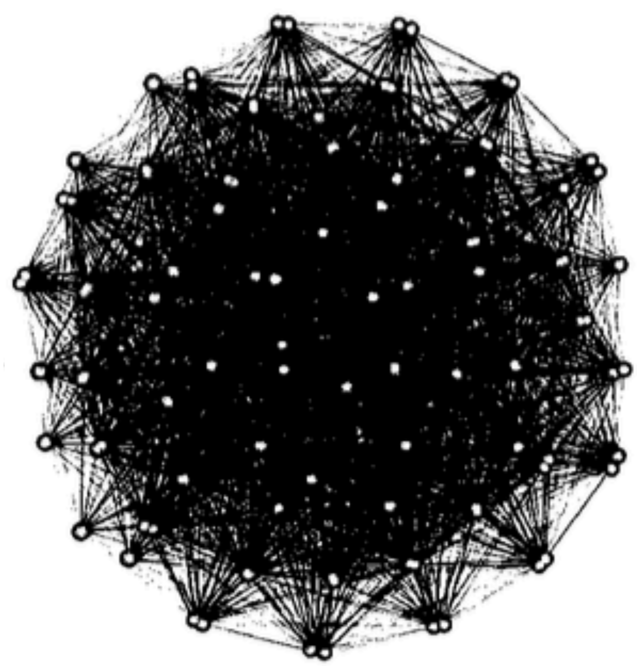


Fig. 3.8 Network typology of the interactions among ecological building fitness measures (Boussabaine 2010).

	Degree	Closeness	Betweenness
Mean	140.738	100	113.003
Std Dev	4.117	0	0.034
Sum	16184.9	11500	12995.336
Variance	16.953	0	0.001
SSQ	2279785	1150000	1468511
MCSSQ	1949.591	0	0.134
Euc Norm	1509.896	1072.38	1211.821
Minimum	131.114	100	112.995
Maximum	151.672	100	113.222
Centralization	0.0628		
Heterogeneity	0.0087		
Centralization index	0.00002		
Density	0.99		
Clustering coefficient	1.00		

Fig. 3.9 Typological characteristics of the ecological building fitness measures (Boussabaine 2010)

Each of the measures presented in Fig. 3.9 represents typological characteristics of the built network. Those measures are analysed by the research to uncover the complex structure of the ecological building design.

3.3.6. Analysis of knowledge diffusion in networks

Network modelling techniques have been used by several researchers to model the complexity of information flow and the diffusion of knowledge between the components of the network. This section of the research will review the literature on analysing the knowledge diffusion in networks, as it determines the controllability of the components in the networks in information flow.

According to Canals (2005), the use of network analysis to model the knowledge diffusion in a network has enhanced our ability to utilise the network of organisations and processes. In this research model, the diffusion of knowledge using network techniques and the results of the research highlight the significant factors of knowledge diffusion in the modelled networks. In addition, the research used the network results to analyse the diffusion of knowledge in the case studies. This method of using network modelling to model the information flow and knowledge diffusion has significantly enhanced the efficiency of knowledge diffusion investigation.

3.3.7 Analysis of the network components' resilience to certain design phenomena

Several researchers have presented techniques of modelling complex systems using network techniques to investigate a certain phenomenon such as the resilience of systems. This section of the research will review the literature on modelling complex systems using a network.

According to Johansson (2010), there has been a wide use of network modelling applications to model the complex systems; more specifically, for modelling technical systems such as transportation, infrastructure, and telecommunication systems. The research presented the use of network modelling in modelling power systems, transportation systems, and telecommunication systems. Most studies focus on the analysis of the resilience of these systems to a certain phenomenon such as the effect of a disconnection or failure of one of the system's components on the whole system, as well as how systems can be designed to be resilient to this type of phenomenon.

3.4 Conclusion

This chapter has presented the tools used in analysing and modelling the complexity of design, which are significantly enhancing our efficiency to understand complex system design as well as the interactions between such a system's components. The chapter has reviewed several research analyses of complexity in the design process and complexity of the designed product. In addition, in this chapter the research has determined the tools that are going to be used to model building complexity. The tools that are going to be used to uncover the complexity of the building design process and the complexity of building systems design are the design structure matrix and network modelling and centrality measures. The chapter has introduced the network definitions and science as well as the concept of the network typological characteristics, which are going to be, uncovered for each of the design process stages and the building systems design. In addition, the chapter has introduced the analysis of the knowledge diffusion of the building design process and the resilience of building systems design.

CHAPTER 4: THEORETICAL FRAMEWORK OF COMPLEXITY IN BUILDING DESIGN

4.1. Introduction

This chapter of the research will present the theoretical framework of the research, which is focusing on the modelling of complexity in the building design process and building design product. The chapter will review the importance of this research to the field of the design process by indicating the factors that increase the complexity of the building design process as well as the complexity in designing building systems. In addition, the chapter will present the methods of modelling the complexity of aspects of the building design process interactions and the significance of this modelling to analyse the diffusion of knowledge in the process and the controllability of the knowledge diffusion in the design process networks. Moreover, the chapter will present the methods of modelling the complexity of building systems design in the interactions in each component of each of the building's systems, as well as indicating the significance of this modelling for analysing and assessing the resilience of these building systems to certain phenomena that happen in their components.

4.2. Factors of complexity in the building design process

As presented in the previous literature review chapter, the research has reviewed several complexity factors that increase the complexity of the design process. Those factors are significant and need to be taken into consideration when modelling the design process.

The following section will discuss these factors and will also highlight the focus of this research, which is to model and analyse the building design process based on a case study, which is the modelling of the knowledge diffusion in this process. The following figure (Fig. 4.1) indicates the factors that increase complexity in the building design process under three main categories of building design process complexity, which are the complexity of modelling the design process, the complexity of establishing design process components, and the complexity of information flow and diffusion of knowledge in the building design process. Each of the complexity categories highlights the factors that increase the complexity in it. However, the research will focus on modelling and analysing the complexity of information flow and knowledge diffusion in the building design process because it is the most significant complexity due to the large number of aspects that are involved in it, as well as the small number of studies that have focused on this topic.

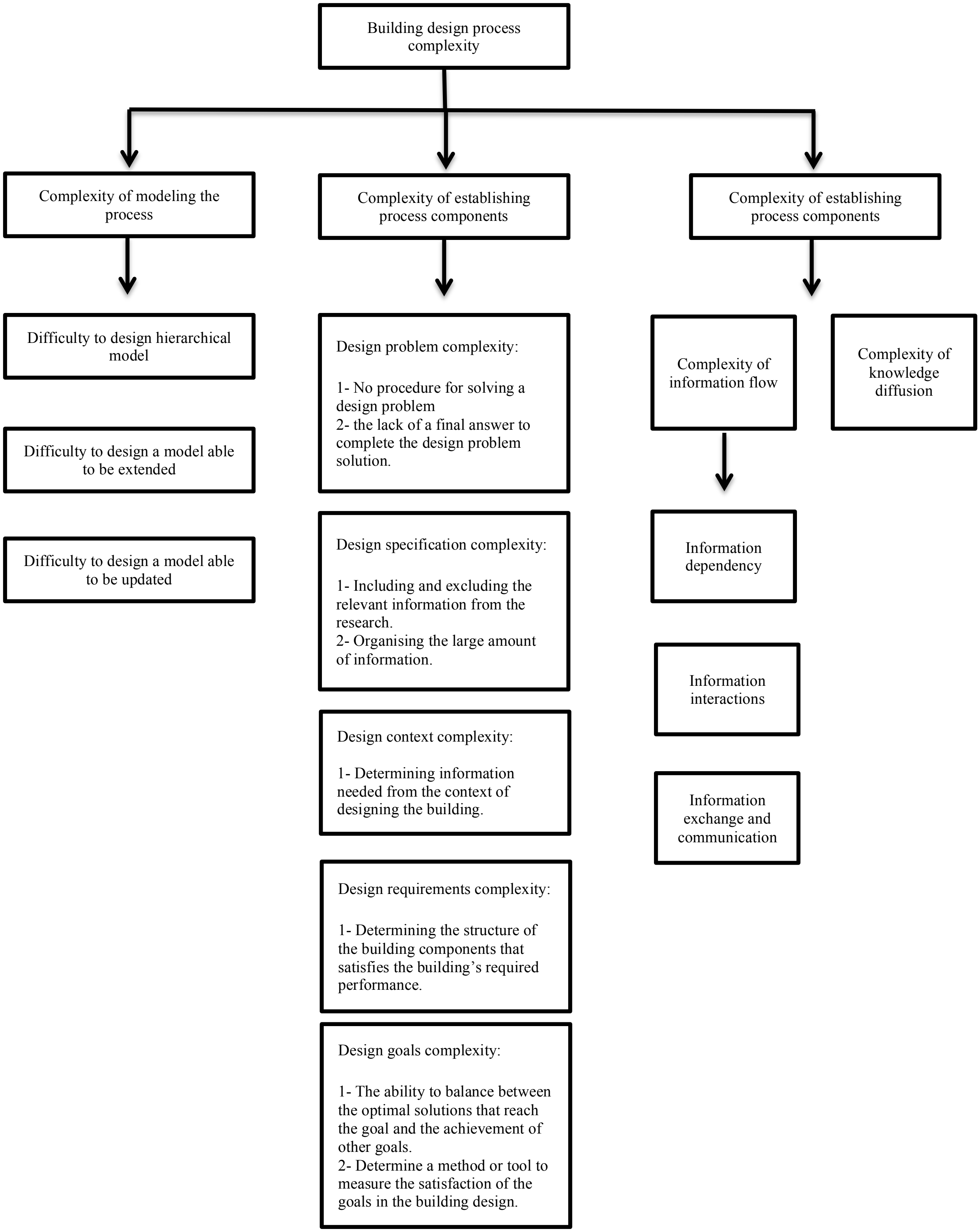


Fig. 4.1 Factors that increase the complexity of the building design process

4.2.1 Modelling the complexity of knowledge diffusion in the building design process

In this section, the research will indicate the methods of modelling the flow of information and the knowledge diffusion in the building design process. Three main aspects of the building design process play a role in information flow and diffusion of knowledge: the design tasks, design team, and design process components. Fig. 4.2 indicates how information flows through the design process towards the establishment of the design process outcomes or components. The following subsections explain the three aspects of the building design process that control the diffusion of knowledge.

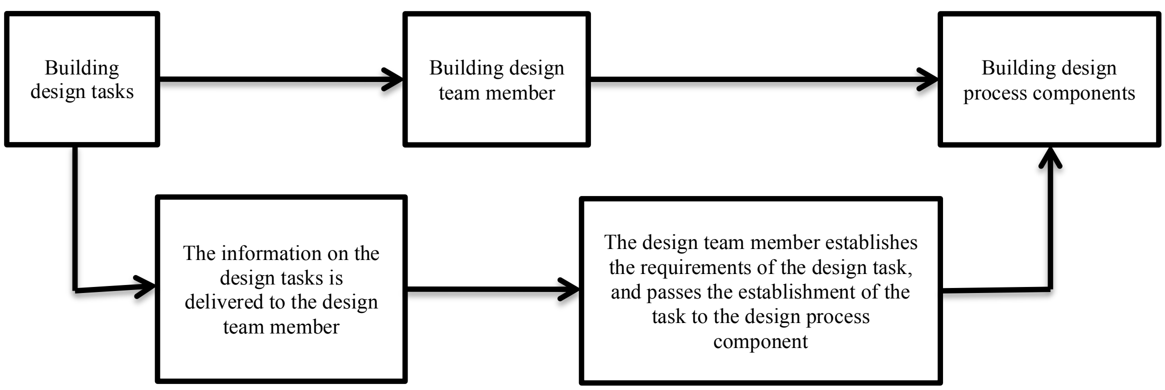


Fig. 4.2 Methods of modelling the three aspects of building design process knowledge diffusion

4.2.1.1 Building design process tasks

According to the Oxford Dictionary, a task defined as "A piece of work to be done or undertaken" (Oxford 2014). This definition indicates that a task is part of a piece of work, which consists of several tasks that need to be performed in order to accomplish the required work. In this research, the focus is on the building design process, which consists of several stages, and each stage consists of several tasks. The design process stage is defined in the Oxford Dictionary as a “step in process or development” (Oxford 2014). This definition indicates that a design stage is part of a process moving forward towards the accomplishment of the building or the outcomes of the design.

4.2.1.2 Building design process team

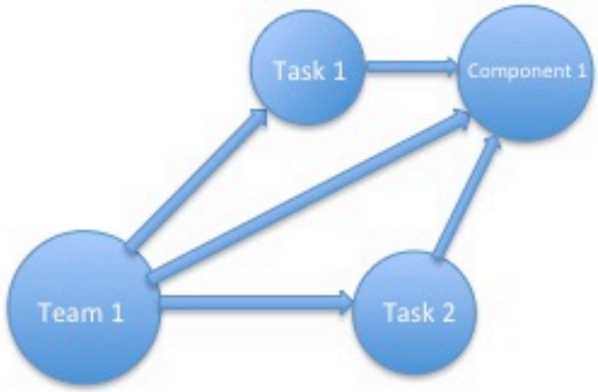
The second aspect that will be investigated and modelled in this research in terms of its interactions is the design team members’ interactions with the design tasks as well as their interactions with the components of the building design processes. The building design team is defined differently from various views in the literature. However, this research will define design team members as part of a project team who cooperate with each other throughout the design process stages to produce a building design. According to CIOB (2014), projects involve a large number of people; this could be more than thousand team members in a large-scale project. The structure of this team changes throughout the building design process stages: some of the design team are involved for a short period of time to bring specific knowledge or experience to the project; however, the project team is involved in the project design process from the beginning of the project until the end.

4.2.1.3 Building design process components

The third aspect of the building design process is the building design process components, which are the outcomes of the design process. In the building design process there are several outcomes that build up the final outcome, which is the technical design or the working drawings. These components vary from stage to stage and they are established and begin in different stages and are finalised in different stages of the process. This research will identify the design process components that are considered an outcome of the building design process, and it will determine their place throughout the building design process, from the stage at which they began to the stage at which they became established.

4.2.2 Modelling the interactions of the building design process aspects of information flow and knowledge diffusion

The modelling techniques of the building design process aspects of information flow and knowledge diffusion that are used in this research are the network modelling methods. According to Mitchell (2009), a network is a collection of nodes and links that connect the nodes to each other. The nodes represent an individual aspect of the network and the links connects those aspects together. In this research, the modelling of the design process aspects as a network consists of nodes, which present the aspects, and the links between the nodes, which is the information that is passing through the aspects of the building design process. An example of the modelling is shown in Fig. 4.3, which indicates the methods of connecting the design tasks to the design team members and to the design process components. As shown in Fig. 4.3, diagram 1 indicates that design team member 1 has to accomplish a design task to establish design component 1; however, in diagram 2 the typology has changed: design team member 1 cooperates with design team member 2 and they accomplish one task in which they interact, which is task 2, and each has performed a task by her/himself: design team member 1 performed task 1 and design team member 2 performed task 3, and all those three tasks have established design component 2.



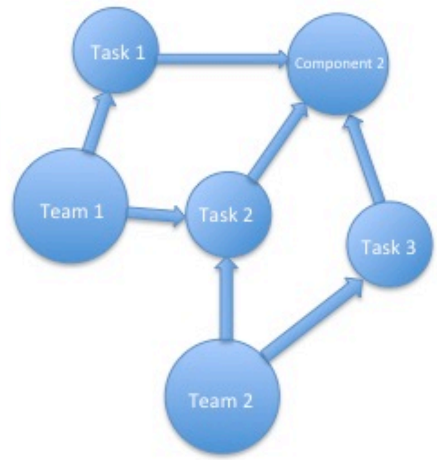


Diagram 1 Diagram 2

Fig. 4.3 Different typologies of information flow from design tasks to design team members and design process components

4.2.3 Outcomes of modelling the information flow and knowledge diffusion of the building design process

There are several outcomes from the use of network modelling techniques to model the information flow and knowledge diffusion in the building design process. They are extremely efficient in uncovering the complexity of the building design process and help to improve the outcomes of this process. Those outcomes are listed below:

1- Determine the paths of information flow in each stage of the building design process.
2- Determine the aspects that are controlling the diffusion of knowledge in the building design process stage.
3- Determine the information flow that is required to establish an outcome from design tasks.

4.3 Complexity factors in designing building systems

In the previous chapters the reviews of the complexity factors that increase the complexity of building systems design. It is important to take these factors into consideration when designing building systems. This section of the research discusses these factors, as well as the research focus on modelling and analysis, which is based on a case study of a building. Fig. 4.4 highlights the factors that increase the complexity of designing building systems under the main building system categories, which are the ability to design building systems to be resilient to a certain phenomenon that happens in each design. The research focus in terms of designing the building systems is on the ability to design a building's systems to be resilient to fire escapes, its structural systems to be resilient to earthquake effects, to be resilient to the needs of the architectural spaces in the building envelope, and the resilience of the HVAC, power system and lighting system to failure of components that provide air supply or power. Due to the importance of designing building systems to this certain resilience level, the research will assess these resilience design needs using the network modelling method.

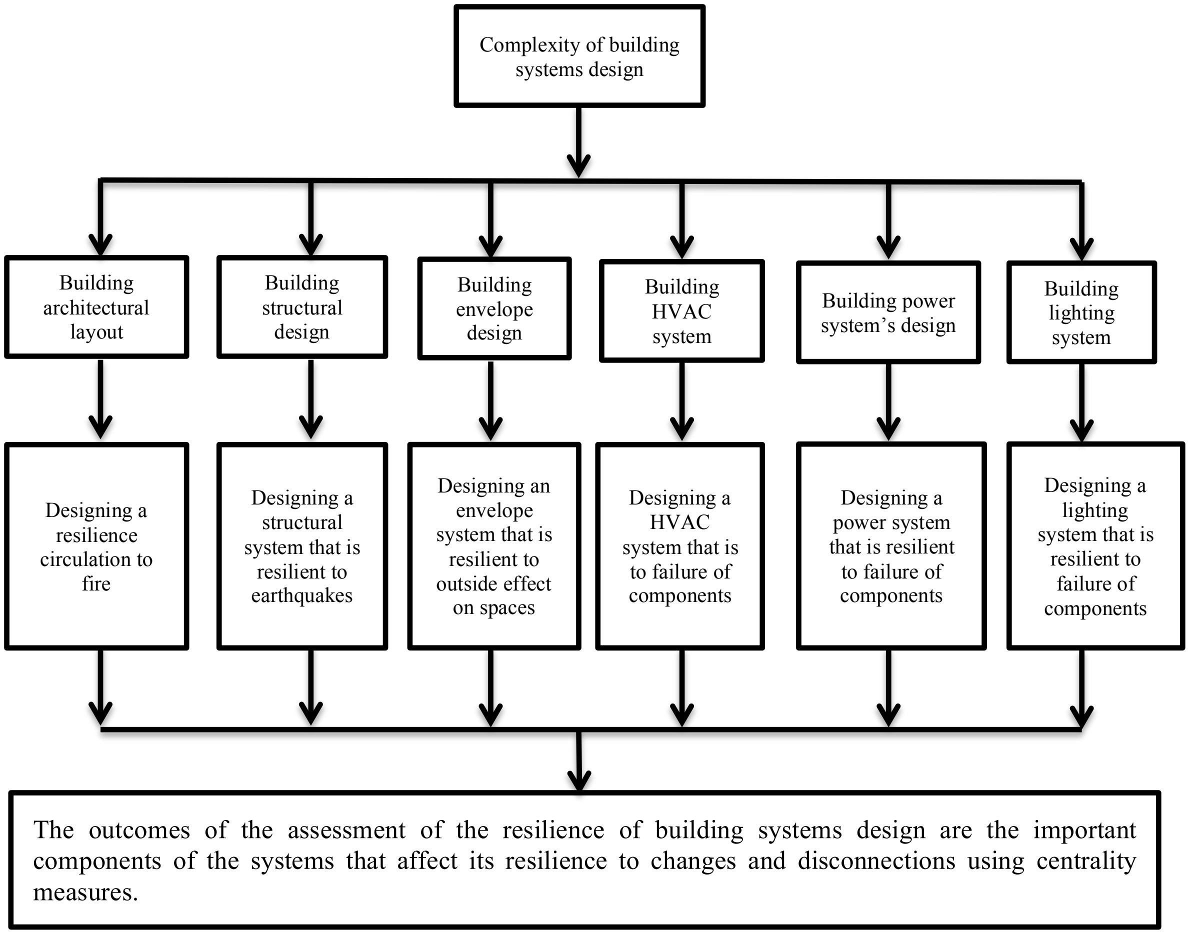


Fig. 4.4 Complexity factors in building systems design

4.3.1 Modelling the complex interactions of building systems design

This section of the research will indicate the methods of modelling the interactions between the building system components. In each system, there are categories of components that play the role of system connectivity and functionality; those components interact and connect to form the building's systems. This research will model the interactions between the building system's components using the network modelling techniques by extracting the components from a case study and modelling them in the form of a network where the nodes are the components of the system and the edges are the physical interactions between those components. Fig. 4.5 shows the method used to model the interactions of these building system's components in order to assess the system's resilience to a certain phenomenon.

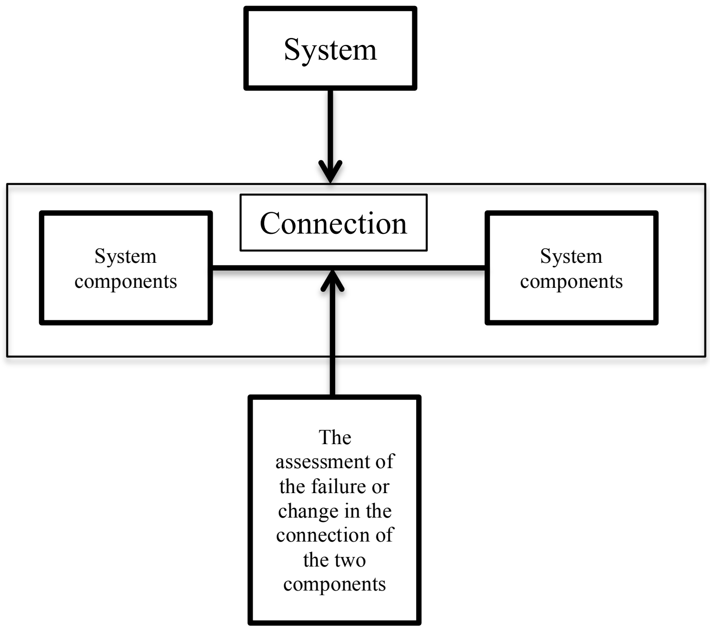


Fig. 4.5 Assessment of interactions between the system components

4.3.2 Modelling the interactions of the building systems design

The modelling technique of the building systems design that is going to be applied in this research is the network modelling method. The network consists of nodes and edges; the nodes represent the components of the building systems and the edges indicate the connectivity between those components. The following section will indicate the methods of modelling the interactions of each system's components, which are the architectural systems, structural, envelope, HVAC, power, and lighting systems' components.

4.3.2.1 Methods of modelling the interaction of the architectural system components

Modelling the architectural components of the building systems in this research focuses on the significance of the interactions between the components of the systems. For example, there are four significant components in the architectural systems that are important to model in order to assess the building's circulation flow in case of fire. Those components are the architectural spaces, the circulation spaces that link the architectural spaces, the elevators, and the fire escape stairs. These interacting components are the important aspects in modelling the circulation flow because they interact to 'flow' the people through the building. In addition, there are three types of links between those components, which are the links between one space and another, which indicates a strong relation between these two spaces in terms of their closeness to each other, the links between the architectural spaces and the circulation spaces connected to them, and the links between the circulation spaces and the elevators and the stairs that the building users use to move from one space to another or to enter and exit the building. Fig. 4.6 shows the method of modelling the interactions between the building's architectural systems components.

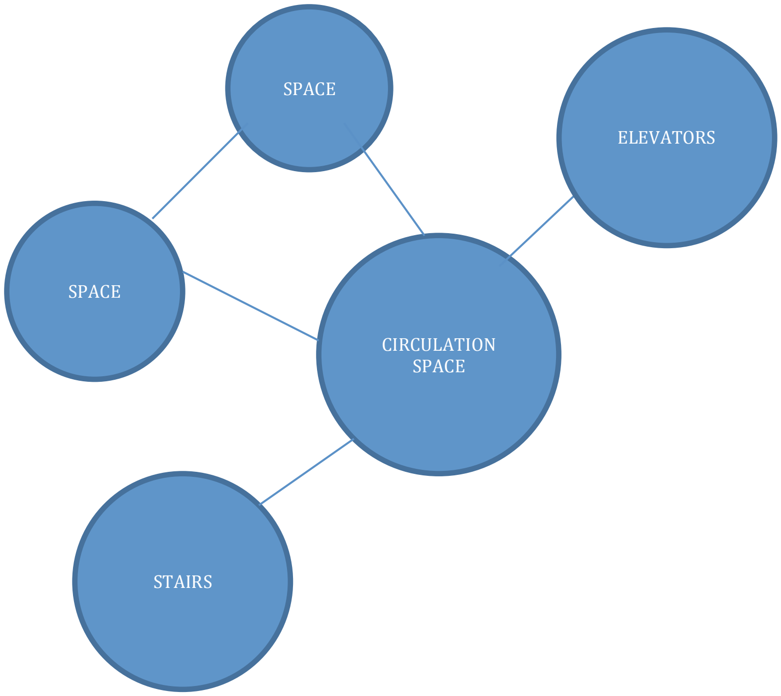


Fig. 4.6 Modelling of the circulation flow in the building

4.3.2.2 Methods of modelling the interaction of the structural system components

Modelling the structural components of the building systems in this research focuses on the significance of the interactions between the components of the systems. There are five significant components of the structural system that are important to be modelled in order to assess the building components' resilience to earthquakes. They are the building's foundations, its columns, the floor slabs, the concrete walls, and the concrete cores. These interacting components of the building structure are the important aspects in modelling the building's skeleton, which needs to resist earthquakes. In addition, there are five types of links between these components, which are the links between the foundation of the building and the columns, the links between the columns of one floor to the floor above, the links between the columns and the floor slabs, the links between the floor slabs and the concrete cores, and the links between the concrete walls and the concrete walls. It is very important to model the interactions of these components because the effect of an earthquake on one component of the structural system can possibly be propagated to other components that are connected to it. Fig. 4.7 shows the method of modelling the interactions between the components of the building's structural system.

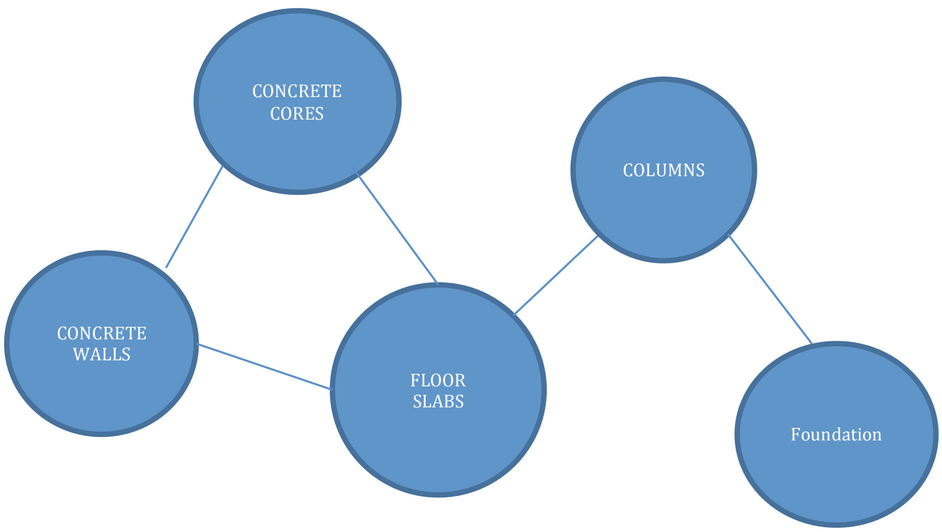


Fig. 4.7 Modelling the structural components' interactions in the building

4.3.2.3 Methods of modelling the interaction of the envelope system components

Modelling the components of the building's envelope system in this research focuses on the significance of the interactions between the system's components. Two types of components are important to model in order to assess the envelope system's resilience to outside effects. They are the building's windows and its architectural spaces. The interactions of these two components are the important aspects in determining the source of outside effect to the building spaces. In addition, there are two types of links between these components, which are the links between the one window structure to another window structure, and the links between the windows and the architectural spaces. It is very important to model the interactions between these components because they affect the relation between the building's outdoor and indoor environments. Fig. 4.8 shows the method of modelling the interactions between the components of the building's envelope system.

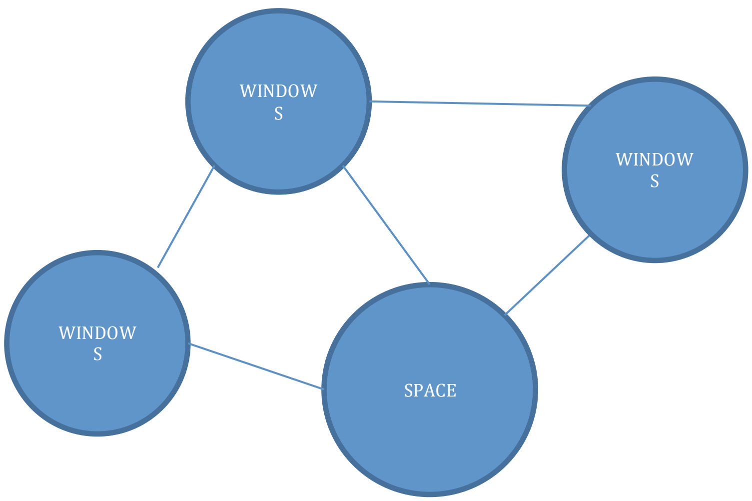


Fig. 4.8 Interactions between the envelope system components

4.3.2.4 Methods of modelling the interaction of the HVAC system components

Modelling the components of the building's HVAC system in this research focuses on the significance of the interactions between the system's components. Four types of components in the HVAC system's modelling are important to be modelled in order to assess the system's resilience to a failure or change that happens in any of its components. They are the HVAC rooms, the architectural spaces that are supplied with air from the HVAC system, the duct that supplies the air to the building spaces, and the return ducts that return the ducts to the HVAC system. In addition, there are four types of links between this system's components, which are the links between the spaces and the supply ducts, the links between the spaces and the returns ducts, the links between the

HVAC rooms and the supply ducts, and the links between the HVAC room and the return ducts. It is very important to model the interactions between these components because they determine the flow of the air and the returned air in the building's HVAC system, and when this flow is modelled it gives a very significant outcomes of controlling the failure of the components in the system as well as the disconnection of a components in the system. Fig. 4.9 shows the method of modelling the interactions between the components of the building's HVAC system.

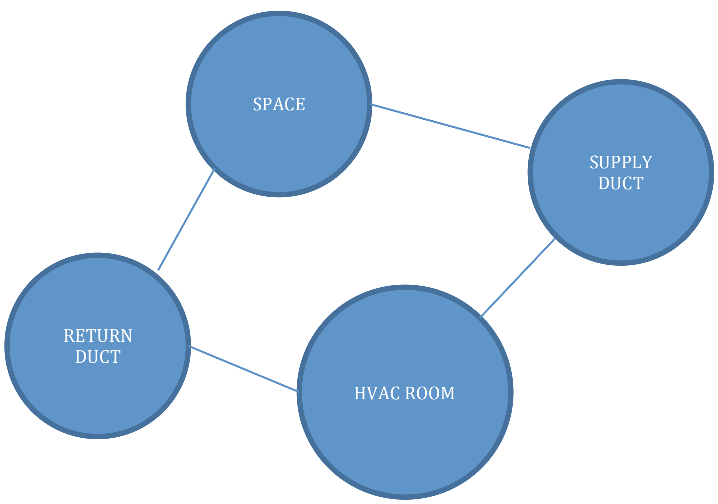


Fig. 4.9 Modelling of interactions between the building's HVAC system components

4.3.2.5 Methods of modelling the interaction of the power system components

Modelling the components of the building's power system in this research focuses on the significance of the interactions between the system's components. There are five types of components in the power system modelling that are important to model in order to assess the resilience of the power system to a failure or change that happens in any of its components. They are the generator, the main panels room, which provides the spaces with electricity, the architectural spaces of the building, the power lines, which provide power to the receptacles, and the receptacles themselves. In addition, there are six types of links between the components of the power system, which are the links between the generator and the main panels room, the links between the main panels room and the power lines, the links between the power lines and the spaces, the links between the receptacles and the power lines, and those between the receptacles and the spaces. It is very important to model these components because they determine the flow of electricity in the building; this flow model gives the very significant outcomes of controlling the failure of the components in the system as well as the disconnection of a component in the system. Fig. 4.10 shows the method of modelling the interactions between the components in the building's power system.

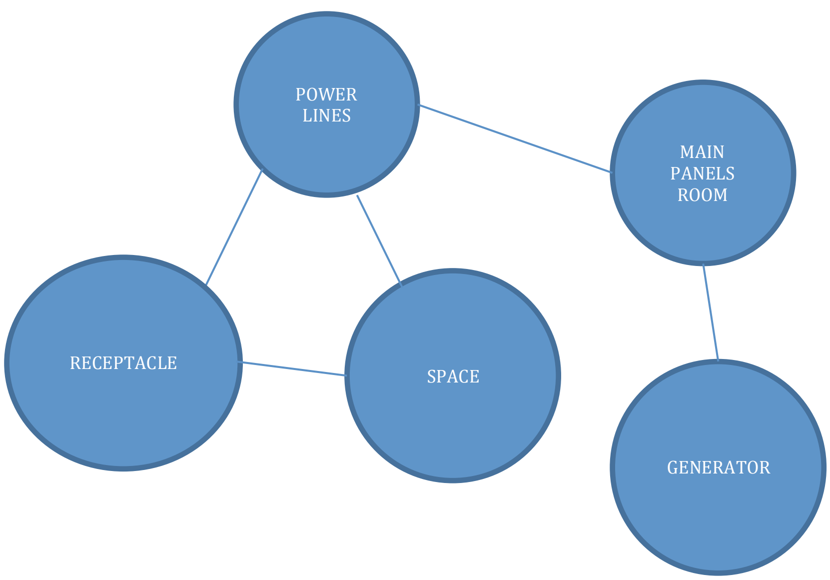


Fig. 4.10 Modelling of interactions between the building's power system components

4.3.2.5 Methods of modelling the interaction of the lighting system components

Modelling the components of the building's lighting system in this research focuses on the significance of the interactions between these components. There are five types of components in the lighting system modelling that are important to be modelled in order to assess the system's resilience to a failure or change that happens in any of its components. They are the generator, the main panels room, which provides the electricity, the architectural spaces of the building, the lighting lines, which provide power to the lighting fixtures, and the lighting fixtures themselves. In addition, there are six types of links between the components of the lighting system, which are the links between the generator and the main panels room, the links between the main panels room and the lighting lines, the links between the lighting lines and the spaces, the links between the lighting fixtures and the lighting lines, and those between the lighting fixtures and the spaces. It is very important to model these components because they determine the flow of electricity in the building to provide the lighting system; this flow model gives very significant outcomes of the controlling to the failure of the components in the system as well as the disconnection of a component in the system. Fig. 4.11 shows the method of modelling the interactions between the components of the building's lighting system.

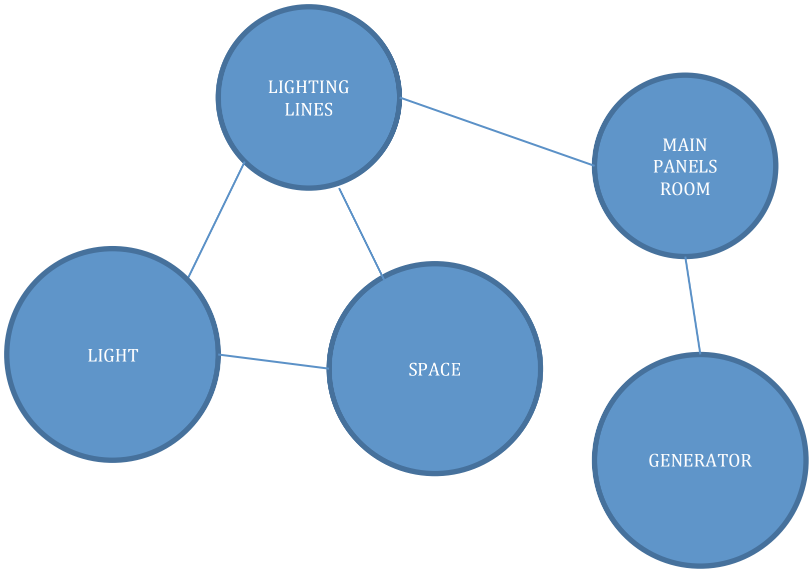


Fig. 4.11 Modelling of interactions between the building's lighting system components

4.3.3 Outcomes of modelling the building systems design complexity

There are several outcomes from the use of networks to model the interactions of the building system's components. They are very significant in enhancing our ability to uncover the complexity of the building system's design and improve the outcomes of the building design. These outcomes are listed below:

1- Determining the resilience of the circulation of the building design to several phenomena such as the resilience to a fire and the ability to evacuate the building without affecting the building users.
2- Determining the resilience of the structural system of the building to several phenomena, such as its resilience to the effect of an earthquake on a certain structural component and the propagation of this effect to other structural components.

3- Determining the resilience of the envelope system to provide the outdoor needs of the building to the architectural spaces, and determining the resilience of the envelope to prevent any negative outdoor effects on the architectural spaces.
4- Determining the resilience of the HVAC system of the building to failure of one component of the system as well as determining the effect of the system's functionality to the disconnection of this component to the architectural spaces.
5- Determining the resilience of the power system of the building to failure of one component of the system as well as determining the effect of the system's functionality to the disconnection of this component to the architectural spaces.
6- Determining the resilience of the lighting system of the building to failure of one component of the system as well as determining the effect of the system's functionality to the disconnection of this component to the architectural spaces.

4.4 The value of network modelling used to uncover the complexity of a design

The theoretical framework of this research highlights the factors that increase the complexity of building design, which are listed in two main categories: the complexity of the building design process and building systems design. The theoretical framework indicates that the most significant factor that increases the complexity of the building design process is the efficiency of information flow and diffusion of knowledge through the design process, so the research highlights three aspects that are very significant in modelling the flow of information in the building design process to uncover its complexity and determine the controllability of knowledge diffusion through the process towards the establishment of the process outcomes or components of the process. Those aspects are the design tasks, the design team and the design process components.

Modelling the flow of information through these three aspects using network modelling techniques for the building design process significantly enhances the ability to achieve the goal of uncovering the complexity of information flow and diffusion of knowledge. In this research, the modelling of the design process network is going to use the case study of a building design process guide, which is the RIBA plan of work, to extract the design tasks and the design team who are responsible for establishing the design tasks as well as the design process components that are established by accomplishing the design tasks. In addition, the research will use the network modelling techniques and measures to indicate the flow of information and knowledge diffusion as well as the controllability of these processes through the design stages.

The theoretical framework indicates the factors that increase the complexity of designing building systems. Those systems are the architectural systems, the structural system, the envelope system, the HVAC system, the power system, and the lighting system. Each one consists of components that interact to carry out their functions; however, the systems need be designing with an assessment of their resilience to certain phenomena that affect their functionality. Furthermore, the architectural system has to achieve an efficient circulation flow in case of fire; the structural system has to be designed to be resilient to several effects, such as earthquakes, and to be resistant to the propagation effect of the failure of one or more structural components; the envelope system has to efficiently link the outdoor and indoor spaces with the efficiency of providing and preventing; the HVAC system, and the power and lighting systems have to be resilient to the effect of failure of any of their components. Therefore, this research will use the network modelling techniques and measures to assess the resilience of these systems to certain design phenomena that can affect the functionality of that system. Using a case study building to model the interactions of the systems' components and assessing the resilience of those systems, the research will identify the design strategies to prevent and reduce those effects on the systems' functionality.

4.5 Conclusion

The chapter has introduced the theoretical framework of the complexity of building design. This theoretical framework presents the factors that increase the complexity of the building design process and building design product. These factors are determined from an investigation of the literature on the building design process and building system design. In addition, the chapter has presented a model of the information flow between the three main aspects of the building design process, which are the design team, design tasks, and design process components. The chapter has also indicated the methods of connecting the aspects of the building design process to each other to model the information flow of the design stage. In addition, the chapter has presented the methods of connecting the components of the building systems to each other to uncover the complexity of building system design.

CHAPTER 5: RESEARCH PROCESS AND METHODOLOGY

5.1. Introduction

This chapter presents the methodology and the research process that are applied in this research to model the complexity of the building design process, building architectural design, and building system design. The chapter will explain the research process and the methods that are going to be used to achieve the goal of uncovering the complexity of the building design process and of building design. Moreover, it will explain the methods of modelling the interactions between the aspects of the design process and the knowledge diffusion in the building design process, and the software and measures that are going to be applied to the design process stages to determine the analysis for the design process case study. In addition, the chapter will explain the methods of modelling the interactions between the building system design components and the connectivity between them, and the software and measures that are going to be used to determine the analysis of the case study.

5.2 Research methodology

The research methodology in this research is a design research methodology that applies scientific approaches and methods to solve the research problem, which seeks to uncover the complexity of the building design process and product. The methodology answers the research questions by using a network analysis and modelling techniques as tools to model the case studies of the building design process and product. According to (Brooks

1987) and Von Alan (2004), the design research methodology is an appropriate way of solving a wicked research problem. The research problem in this research is determined as a wicked problem because it meets the criteria that Von Alan (2004) stated in the description of a wicked research problem, which requires a specifically designed process to approach and solve it.

Several studies have used the design research methodology approach, especially in the engineering domain. In this research, the methodology will be designed based on three criteria, which are the design of the research as an artefact, the research problem relevancy, and design as a research process.

5.2.1 Design research as an artefact

The term design problem solving means presenting the problem with a clear and transparent solution. This research presents the problem of the research of the building design processes and product complexity as well as proposing a method of solving this increasingly complex problem using the network analysis software tool to uncover the complexity of interactions and information propagation. March (1995) described four ways of designing science research, which are constructs, models, methods and implantations. Constructs are the tools used to design the problem and find the solution to it. In this case, the research used the design structure matrix to capture the complexity of the design process and the building product. Modelling is a more advanced way of constructing the design problem and its solution, which was solved in this research by using the network modelling techniques, which present the network diagrams. The method is used to detect the network's interactions and patterns as well as to determine the general typological characteristics of the building design process stages, and building systems design. The implementation is finally applied by the investigation of specific knowledge diffusion in a design process stage and determining the effect of the resilience of the system to a certain type of change in the components.

5.2.2 Research problem relevancy

According to Von Alan (2004), a design research methodology explains the problem and how to address and solve it. In addition, the difference between the problem and the solution is the current state of the system and the state of achieving the goal. The problem in this research is located in the stage of designing the building from the strategic definitions stage to the technical design stage and, in terms of the building systems; it is located in the design of the interactions between the systems' components. This indicates that the research problem is mainly determined by its relevance to the knowledge of design and practice that contributes in.

5.3 Research process

The research process consists of six main steps that are used to uncover the complexity of the building design process. This starts with reviewing the literature of the building design process complexity and building system design complexity, which leads to identifying the factors that increase the complexity of the building design process and building system design.

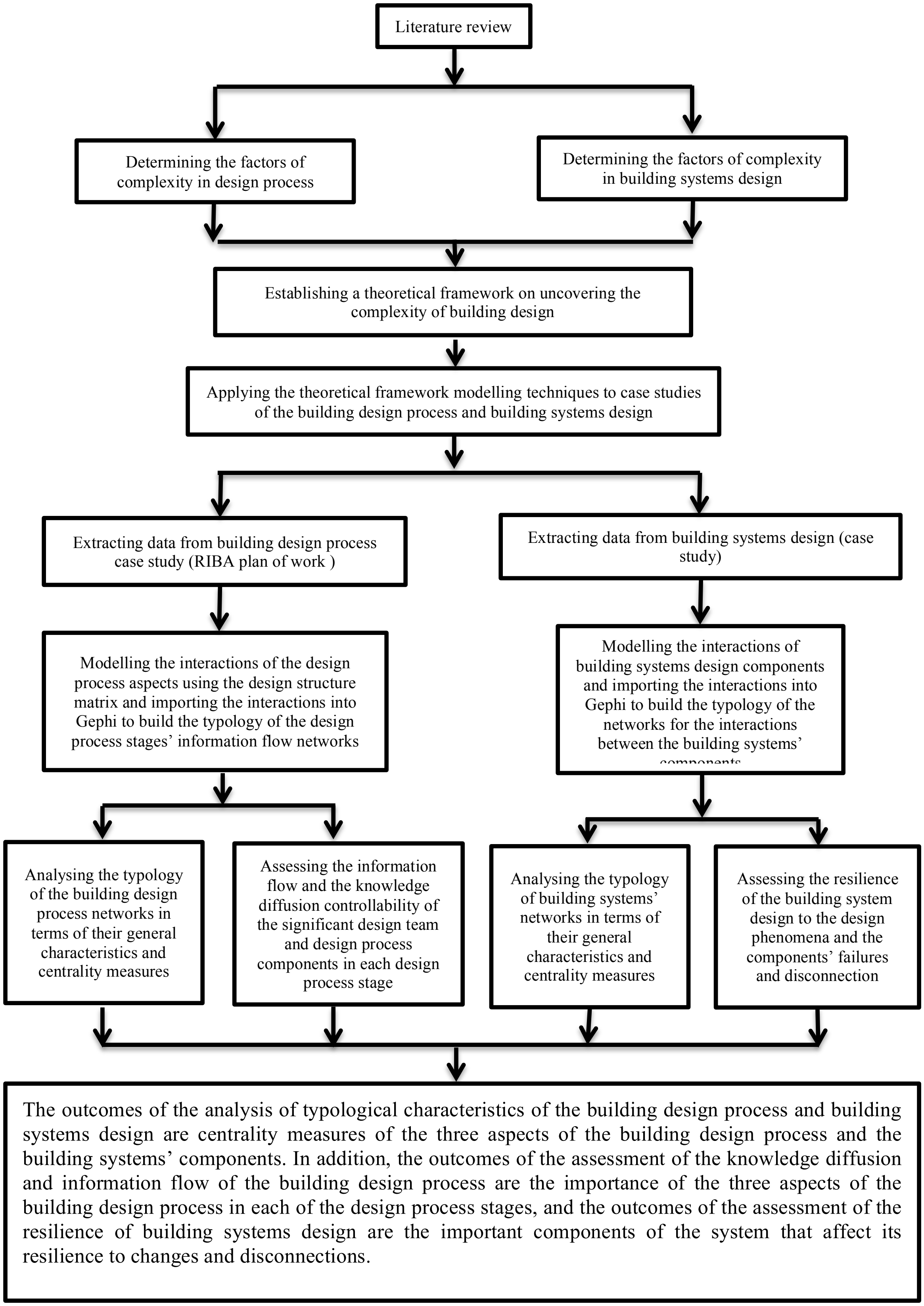

Literature review
Determining the factors of complexity in design process
Determining the factors of complexity in building systems design
Establishing a theoretical framework on uncovering the complexity of building design
Applying the theoretical framework modelling techniques to case studies of the building design process and building systems design
Extracting data from building design process case study (RIBA plan of work)
Extracting data from building systems design (case study)
Modelling the interactions of the design process aspects using the design structure matrix and importing the interactions into Gephi to build the typology of the design process stages' information flow networks
Modelling the interactions of building systems design components and importing the interactions into Gephi to build the typology of the networks for the interactions between the building systems'
Analysing the typology of the building design process networks in terms of their general characteristics and centrality measures
Assessing the information flow and the knowledge diffusion controllability of the significant design team and design process components in each design process stage
Analysing the typology of building systems' networks in terms of their general characteristics and centrality measures
Assessing the resilience of the building system design to the design phenomena and the components' failures and disconnection
The outcomes of the analysis of typological characteristics of the building design process and building systems design are centrality measures of the three aspects of the building design process and the building systems' components. In addition, the outcomes of the assessment of the knowledge diffusion and information flow of the building design process are the importance of the three aspects of the building design process in each of the design process stages, and the outcomes of the assessment of the resilience of building systems design are the important components of the system that affect its resilience to changes and disconnections.

Fig. 5.1 Research process followed to uncover the complexity of the building design process and building system design

5.3.1 Theoretical framework to model the complexity of the building design process and building systems design

The second step of the research process is establishing a theoretical framework that can be applied and used to model the complexity of the building design process as well as the complexity of building systems design. This theoretical framework defines the modelling approach to the design process from a perspective of information flow and knowledge diffusion in the design stage. It determines the way information flows from design tasks to design team members for the establishment of design process components that are part of the outcomes of the design stage, as well as the whole design process. In addition, the theoretical framework defines the modelling approach of the building systems design from the perspective of interactions of the components to establish the functionality of the system. It determines the way components of the building system interact to form building systems. Using network modelling techniques to model the complexity of the building design process and building systems design, the theoretical framework proposes an approach of analysing two aspects on which this this research focuses, which are the modelling of the knowledge diffusion networks in the building design process and the modelling of the building system networks for the purpose of assessing the resilience of the system to certain phenomena. The methods of modelling the networks of the building design process stages and building system design are described in Chapter 4.

5.3.2 Extracting data from case studies

The third step is explaining how data is extracted from case study data; this research uses two case studies, a case study for the building design process, and one for building system design. The first case study that will be modelled is the building design process stages that are based on the RIBA plan of work. The design tasks in this case study will be used to model the interactions of the building design process tasks with the design team, and will also be used to extract the design process components or outcomes. In addition, as mentioned in Chapter 4, the aspects that will be modelled in the building design process are the design team, design tasks, and design process components; therefore, the research will use the design structure matrix to model the interactions between the design process aspects. Fig. 5.1 provides an example of modelling the interactions between the design process aspects. The matrix in Fig. 5.1 shows the method that is going to be used to model the interactions between the three aspects of the building design process where (X) in the matrix indicates the design tasks that a design team member is required to establish and the task part of the design process component. Furthermore, as shown in Fig. 5.1, design task 1 has to be established by design team 1, and this design task is part of establishing design process component 1. The research will list the design tasks of each stage of the design process, determine the design team members who are establishing these tasks and indicate the third interaction of the flow of information, which is the design process components that are part of establishing the particular design task. When the matrix of the five design stages of the RIBA plan of work is generated, the interactions between the three aspects are going to be extracted in the form of a list of interactions. Table 4.1 shows the method that will be used to list the interactions of the matrix in Fig. 5.1. Each interaction point (X) represents three paths of information, which are the interaction between the design task and the design team, the interaction between the design task and the component(s) that establishes a part of all of it, and the interaction between the design team and the design process component(s) that establish a design task.

	Stage design tasks	Design process component 1	Design process component 2	Design process component 3	Design process component 4	Design process component 5	Design team members
DT1	Design task 1	X					The design team member 1
DT2	Design task 2	X				X	The design team member 2

Fig. 5.2 Design structure matrix to model the interactions between the three aspects of the design process.

Table 5.1 Lists of interactions between the three aspects of the design process according to the design structure matrix of Fig. 5.2

Design task 1	**Design process component 1**
Design task 1	**The design team member 1**
The design team member 1	**Design process component 1**
Design task 2	**Design process component 1**
Design task 2	**The design team member 2**
The design team member 2	**The design team member 2**

Design task 2	**Design process component 5**
Design task 2	**The design team member 2**
The design team member 2	**Design process component 5**

The second case study that will be modelled is the building systems design, which is based on a case study of King Faisal Specialist Hospital & Research Centre building in Riyadh, Saudi Arabia. The modelling of this case study's systems is based on the six systems described in Chapter 4, which are the architectural system, structural system, envelope system, HVAC system, power system, and lighting system. In addition, the research will model the interactions of each system's components based on the theoretical framework in Chapter 4 for each system component using the building drawings and layouts to model the interactions between each system. The method will be used to model the interactions between the system components, in extracting the system components, and in determining the interactions between the components in a form of list of interactions for each system design. Fig. 5.2 shows the design structure matrix generated from the interactions between the architectural spaces in the basement floor of the case study building. In addition, the list of interactions will be extracted from the matrix of each system of the building, as per the example in Table 5.1.

BASMENT 1	B1SR1	B1SR2	B1SR3	B1SR4	B1CM1	B1CM2	B1WMG1	B1WMG2	B1TO1	B1PM1	B1PLN1	B1SPLN1	B1SG1	B1SG2	B1SG3	B1SG4	B1SG5	B1SG6	B1SG7	B1HVC1	B1HVC2	B1HVC3	B1HVC4	B1SPLN2	B1HVC5	B1HVC6	B1HVC7	B1CIRCU
B1SR1		x					x																					x
B1SR2							x																					x
B1SR3				x				x																				x
B1SR4												x																x
B1CM1																												x
B1CM2																												x
B1WMG1																												x
B1WMG2																												x
B1TO1												x																x
B1PM1																												x
B1PLN1																												x
B1SPLN1						x																						x
B1SG1																												x
B1SG2																												x
B1SG3																												x
B1SG4															x													x
B1SG5																x												x
B1SG6																	x											x
B1SG7																		x										x
B1HVC1																					x							x
B1HVC2	x																											x
B1HVC3					x																							x
B1HVC4												x																x
B1SPLN2																												x
B1HVC5																								x				x
B1HVC6						x																						x
B1HVC7			x																									x

Fig. 5.3 Design structure matrix used to model the interactions between architectural spaces of the basement floor of the building case study.

5.3.3 Importing the interactions lists using Gephi to model the networks

The third step of the research process is importing the interactions lists that are generated from the building design process interactions of each design stage and building the interactions of the systems components into Gephi. After the lists of interactions have been imported into Gephi, it will generate the networks for both building design process, and building system design. Furthermore, the research will generate five networks for the building design process stages; each stage will be modelled in terms of the flow of information between its aspects. In addition, it will generate six networks of building systems design for the interactions of each system's components, and each system will be modelled based on the interactions of the components in the theoretical framework in Chapter 4. When the findings of the networks are generated, the software will achieve the typology of each of the design process stages as well as the typology of the building system. Those typologies are going to be analysed from a network science perspective. The outcomes from importing the data into Gephi are divided into two parts of the analysis, which are the findings of the typological characteristics and centrality measures of the networks generated from the design process stages and building systems design, and the use of the results and findings of the measures of the networks to assess the diffusion of knowledge of the building design process, and the assessment of the resilience of the building systems design to a certain design phenomenon.

5.3.4 Analysing the findings of the design process, and building systems networks

The analysis of findings from this research case study modelling is divided into three main groups, which are the descriptive analysis of the case studies, the analysis of the general characteristics and the centrality measures of the case studies, and the assessment of the case studies' network models in terms of knowledge diffusion in the building design process and the assessment of the resilience of the building systems design to certain design phenomena. The following sections will indicate the methods of analysing the findings of the case studies.

5.3.4.1 Descriptive analysis of the case studies

This step of the analysis will describe the aspects and the components of the case studies. For example, the descriptive analysis of the RIBA plan of work will explain the design task stages and the aims that need to be accomplished at each stage of the design process.

In addition, it will explain the three aspects of the design process in the theoretical framework chapter, which are the design tasks, design team, and design process components. The description of the design tasks will explain the design tasks of each design process stage. The description of the design team members will explain their work, their background and their responsibility for establishing a design task. The explanation of the design process components will be based on the RIBA plan of work design tasks because the design process components are extracted from the design tasks. Each design process component consists of several design tasks that have to be established by several design team members in order to achieve the goals of the design stage as well as the goals of the whole design process stages. Moreover, the descriptive analysis of the case study of the building systems design will explain each system of the building in terms of its components' interactions in accordance to the theoretical framework in Chapter 4. In addition, the descriptive analysis will exampling the modelling of the building systems in this research, such as the flow of circulation in the building design; the significant components in assessing the building's resilience to the design phenomena will be assessed in this research based on the building systems modelling.

5.3.4.2 Typological characteristics and centrality measures analysis

As explained in the research theoretical model, this research will use the techniques of network modelling to model both the building design process and the building systems design. This modelling will result in several networks for the building design process stages and building systems design. According to Boussabaine (2010), the research has built the typological characteristics of ecological building fitness measures in the form of a network and used several measures for the typology of the networks that simplify the interactions between the dense networks. The use of these measures will significantly enhance the ability to understand the structural interactions within it. The measures used are centrality measures, the network density measure and the clustering coefficient measures. Each of these measures significantly helps in uncovering the structural characteristics of the network typology. The following sections explain the measures that will be used to uncover the complexity of the network typologies of the building design process and building systems design. Those measures are degree centrality measures, closeness centrality measures, betweenness centrality measure, network density, and clustering coefficient.

5.3.4.2.1 Centrality measures

The centrality measures used in this research to analyse the typological characteristics of the network models of the building design process and building systems design are the degree centrality, the closeness centrality, and betweenness centrality. Each of these will be calculated for the nodes of the building design process and building systems design networks. They provide a meaning for the networks of both the design process and the building systems design. The following section will define the three-centrality measures and indicate the interpretation of these measures in the aspects of the building design process and building systems design.

5.3.3.4.1.1 Degree centrality of the building design process network

The networks of the design process stages consist of three types of nodes, which are the design tasks, the design team, and the design process components. The degree centrality of the design task indicates the number of design team members and design process components that are connected to it. The degree centrality of the design team member indicates the number of the design tasks and the design components with which s/he interacts. The degree centrality of the design process component is the number of design tasks and the design team members that are connected to it.

5.3.3.4.1.2 Closeness centrality of the building design process network

The closeness centrality measures the average distance of a node to all the nodes in the network, which indicates its closeness to all nodes in the network. The lower the closeness centrality of a node, the more central it is in the network, so the more important it is in terms of its knowledge diffusion in the design process stage. The closeness centrality of a design task, design team member and design process component indicates the result of calculating the average distance of the node to all the nodes in the network. The closeness centrality of design task, design team member, and design process component indicates how central the design task is in the design process stage to all nodes of the network.

5.3.3.4.1.3 Betweenness centrality of the building design process network

The betweenness centrality measures how often the node in the network is positioned in the shortest path between two nodes in the network. It indicates how often the node works as a bridge to connect two nodes in the network. High betweenness centrality indicates the node's importance in terms of connecting, and delivering and spreading information between the nodes in the network. The betweenness centrality of a design task, design team member and design process component indicates the result of calculating the times the node works as a bridge to connect two nodes in the shortest path between them. The betweenness centrality of design tasks, design team members and design process components in the design process stage indicates the importance of the node in terms of driving information to other nodes in the network or working as a bridge to deliver information in the design process stage.

5.3.4.2.1.4 Degree centrality of the building systems design network

The degree centrality of a component in the system indicates the number of components that are connected to it. For example, in the architectural system the modelling techniques is as described in Chapter 4, which connects the spaces of the building in terms of their closeness to each other as well as linking them to the circulation spaces and the circulation components such as stairs and elevators. Thus, the degree centrality of an architectural space will be the number of spaces that are connected to it plus the number of other circulation aspects that are connected to it.

5.3.3.4.1.5 Closeness centrality of the building systems design network

The closeness centrality measures the average distance of a node to all nodes in the network. These measures in building systems design indicate the importance of the component in terms of designing the building system. As the node's closeness centrality decreases, this indicates that the node is more central in the network, so it is more important in knowledge diffusion and connecting components to each other. The closeness centrality of a building system component indicates how central this component is to all other components in the system.

5.3.3.4.1.6 Betweenness centrality of the building systems design network

The betweenness centrality measures how often the node is positioned in the shortest path between two nodes in the network. It indicates how often the node works as a bridge to connect two nodes in the network. High betweenness centrality indicates the importance of the node in terms of connecting, and delivering and spreading information, power, air, and lighting between the nodes in the network. The betweenness centrality of a component in the building system design indicates the results of calculating the times the component worked as a bridge to connect two nodes in the shortest path between them. It indicates the importance of the components of the building system in terms of passing information, power, light, circulation flow, and air through the network.

5.3.3.4.2 General characteristic of the centrality measure in the building design process

The general characteristic of the design stage network provides a calculation of the overall nodes' results. It consists of a table that calculates the mean of the results of all nodes' degree centrality, closeness centrality, and betweenness centrality. The reason for calculating the mean of the degree centrality measures is to give an indication of the relationship between the numbers of nodes to the number of average interactions in the network of the design process stage. The reason for calculating the average closeness of all the nodes in the network is to give an indication of how close the nodes are to each other in the network, which indicates how fast information is spread in the network. The mean of betweenness centrality indicates the importance of the spread of information in the network in terms of all the nodes in the network. It gives the average times the node works as a bridge to connect two nodes in the network or passes information through the network. In addition, it calculates the standard deviation of the results of all nodes in the network. A standard deviation close to 0 indicates that the results of the nodes are close to the average and are close to each other. However, an increase in the number of standard deviations indicates that there are a variety of results for the nodes in terms of degree, closeness, and betweenness centrality. Moreover, the sum results for the nodes are the results of adding the nodes' results. The sum result of the degree centrality indicates the number of interactions between the nodes in the network; the sum result of the closeness centrality is the result of adding the results of closeness of all nodes in the network; and the sum result of betweenness is the result of adding the results of betweenness of all nodes in the network.

5.3.3.4.3 General characteristic of centrality measure in building systems design

The general characteristic of building systems networks is giving the overall results for the nodes. It consists of a table that calculates the mean of the results of all nodes' degree centrality, closeness centrality, and betweenness centrality. The reason for calculating the mean of the degree centrality measures is to give an indication of the relationship between the number of nodes and the number of average interactions in the network of the building systems design. The reason for calculating the average closeness of all the nodes in the network is to give an indication to how close the nodes are to each other in the network, which indicates how close the components of the building system are to each other.

The mean of betweenness centrality indicates the importance of the spread of power, light, circulation flow, and air in the network in terms of all the nodes in the network. It gives the average times the node works as a bridge to connect two nodes in the network or passes power, light, circulation flow, and air. In addition, it calculates the standard deviation of the results of all nodes in the network. A standard deviation close to 0 indicates that the results of the nodes are close to the average and are close to each other. However, an increase in the number of standard deviations indicates that there are a variety of results for the nodes in terms of degree, closeness, and betweenness centrality. Moreover, the sum results for the nodes are the results of adding the nodes' results. The sum result of the degree centrality indicates the number of interactions between the nodes in the network, the sum result of closeness centrality is the result of adding the results of closeness of all nodes in the network, and the sum result of betweenness is the result of adding the result of betweenness of all nodes in the network.

5.3.4.4 Assessing the networks of the case studies

In this section of the research, the analysis will go further to investigative the significant factors that increase the complexity in the building design process and building systems design. It will investigate the complexity of knowledge diffusion in each building design process stage in terms of the design tasks, design team, and design process components. In addition, the research will assess the resilience of the building systems design in terms of several phenomena that are significant to take into consideration during the design of the building using the methods of network analysis and measures.

5.3.4.4.1 Assessing the diffusion of knowledge in the building design process stages

Based on the analysis of the typological characteristics of the building design process stage, the research will determine the most significant design tasks, design team, and design process components of the building design process stage in terms of their diffusion of knowledge. Moreover, the research will indicate the significance of these design tasks, design team, and design process components in terms of the diffusion of knowledge in the design process stage. Furthermore, it will assess the importance of the information that flows from and to these three aspects, and the effects of failure of information flow from these aspects in the whole design process stage.

5.3.4.4.2 Assessing the resilience in building systems design

Based on the analysis of typological characteristics of the building systems design, the research will determine the important aspects of the building systems to be assessed in terms of their resilience to the design phenomena. These design phenomena the research going to be assessing is each systems design are very significant aspects that increases the complexity of building systems design. The phenomena that will be assessed are the flow of circulation in the building in case of a fire, the effect of an earthquake on the building's structural system, the effect of the outdoors on the indoors of the building, and the effect of the failure or disconnection of components of the HVAC, power, and lighting system.

5.4 Justification of the research process methods and tools

Several methods are used in this research to model and uncover the complexity of the building design process and building systems design. These methods are the design structure matrix and the network modelling and analysis using Gephi. In addition to justifying their selection, this section will also justify the choices of the case studies of the building design process and building product.

5.4.1 Justification of the methods applied to model the networks

The methods used to model the networks of the building design process and building systems design are the design structure matrix and the Gephi software. The reason for choosing the design structure matrix to model the information flow of the building design process and the connectivity of building systems design is because it is a very significant tool for modelling the interactions between groups of components. In addition, it is a very significant tool for organising the list of interactions that have to be imported into Gephi. In addition, Gephi is a software tool that is used to explore and present graphs and networks and to analyse them. The software has several advanced features such as 3D rendering to present large networks. Gephi provides simple access to the network data, especially for filtering, navigating, and clustering. The visualisation of networks has been developed and improved over many years to achieve efficient graph presentation. The visualisation of a network is very significant to help understand the data interactions in the graph. According to Bastian (2009), Gephi is an efficient source for modelling and visualising networks; it can deal with a large number of nodes as well as edges of the network to be illustrated. In addition, the use of Gephi in this research is because of several features that it has, which significantly help to analyse the data of both the building design process and building system design. These features are a clear and efficient visualisation of the interactions between the nodes of networks; the data ranking, which helps to present the data with a choice of parameters, such as degree; the data table, which indicates the results of the centrality measures of each node in the network; the partitioning feature, which helps to rank and present the nodes with similar results in similar colours; the statistic features, which help to calculates the general characteristics of the networks; and filtering, which provides several options such as Ego Network, which helps to model the propagation of information from a specific node in the network.

5.4.2 Justification of the choice of the case studies

Two case studies are going to be modelled and analysed to uncover the complexity of the design process and product. The first case study is the building design process case study, which is the RIBA plan of work. The modelling of the information flow and knowledge diffusion of this case study is going to be established by modelling the interactions of the three main aspects of the building design process: design team, design tasks, and design components. There is a significant reason why this research uses the RIBA plan of work as a case study for the building design process: the RIBA plan of work design process stages are very clearly designed, so that each design team member is assigned a specific design task, which helps to precisely determine the design process three aspects flow of information in each design process stage, which helps to model them as well as link them to the extracted components of the process.

The second case study used in this research to model building design, as a product is King Faisal Specialist Hospital & Research Centre building in Riyadh, Saudi Arabia; BEEAH, planners, architects, and engineers designed the building. The building comprises 20 floor and two basements floors. The basements are used for parking, and the first and the second floors are reception areas. The third, fourth floor, and fifth floors are the dining and shopping areas. The sixth floor is a service space, and the seventh to the twentieth floors are office space. The reason for choosing King Faisal Specialist Hospital & Research Centre building in Riyadh as a case study is that it reflects the complexity of building architectural design in terms of its functional relationships between spaces. The building is a multi-functional building, which makes it very complex in terms of the complexity factors that are taken into consideration in this research. The factor that increases the complexity of the case study building is the flow of circulation, because the building has vertical circulation cores that interact with the circulation flow of the corridors. In addition, this complexity of circulation flow will significantly increase the complexity of way finding in the building as well as the design of fire escape routes. Furthermore, the building is a large building, which makes its systems' designs very complex, such as the structural, the envelope, the HVAC, power and lighting systems.

5.5 Conclusion

The chapter has presented the research methodology and process applied in this research to uncover the typological characteristics of the building design process and building system design as well as to assess the knowledge diffusion of building design and the resilience of the building systems design. The research methodology applied is a design research methodology, which follows certain design processes to uncover the complexity of design. The research process started with a literature review of complexity to determine the factors that increase the complexity of the building design process and building systems design. The process established a theoretical framework that uncovered the complexity of the building design process and building systems design, which determined how to model each of the building design process stages and the building systems. In addition, the research process of extracting data from case studies to model as networks was also explained. The process also described the modelling of the typological characteristics of the building system using a design structure matrix and Gephi software to generate the networks. After generating the networks and indicating the typological characteristics, the process will assess the networks in terms of the information flow and resilience of the design.

CHAPTER 6: THE TYPOLOGICAL CHARACTERISTICS AND THE ASSESSMENT OF KNOWLEDGE DIFFUSION IN THE BUILDING DESIGN PROCESS (BASED ON THE RIBA PLAN OF WORK)

6.1. Introduction

Designing a building requires several decisions that deal with large amounts of information, activities, and team members. In this chapter, the research will uncover one of the significant factors that increase complexity in building design, which is the building design process. The Royal Institute of British Architects' plan of work will be used as a case study to model the information flow and exchange between the three main aspects of the building design process, design tasks, design team, and design process components, which are modelled in this research based on the theoretical framework in Chapter 4. In addition, design tasks, design process components, and design team form the complexity of knowledge diffusion in the building design process, because they interact, connect, and communicate to generate a building design. Moreover, the interactions between them form a complex system that can be studied from a complexity science point of view in order to enhance the efficiency of modelling the building design process. The aim of this chapter is to model the complexity of information flow and interactions between the three aspects of building design process using a new modelling approach, which are the network modelling techniques. This modelling will result in a model of information flow for each design process stage that determines the interactions and the information flows in this stage of the building design process. Moreover, this chapter will analyse the complexity of the building design process using three main approaches, which are the descriptive analysis of the three aspects of the building design process (design tasks, design team, design process components) based on the RIBA plan of work; the uncovering of the typological characteristic of the design process stages' networks, which indicates the importance of information flow from and to the three aspects of the building design process; and analysis and assessment of the important aspects of the building design process aspects in terms of their controllability of knowledge diffusion in the design stage.

6.2. Descriptive analysis of the design process stages based on the RIBA plan of work

This section of the research describes the five design process stages of the building design process based on the RIBA plan of work, which are strategic definition stage, preparation and brief stage, concept design stage, developed design stage, and technical design stage.

6.2.1 Strategic definitions stage

In this stage, the core objectives that required to be established are the business case and the strategic brief, which are very significant design process components. This stage mainly focuses on ensuring that the business case and the strategic brief take into consideration all the client's requirements before the establishment of the initial project brief. This may require viewing several sites of the building (Ostime 2013). In addition, the matrix in Fig. 6.1 indicates the design tasks that are assigned for the design team and the design process components that the design tasks are establishing. The matrix in Fig.

6.1 indicates that the strategic definition stage requires 15 design tasks to initialise and establishes five design process components, which are the business case, assembling and monitoring the design team, project programme, previous projects' feedback, and strategic brief. In addition, eight design team members are needed to accomplish these design tasks.

1	Strategic Definitions stage	Business case	assembling and monitoring the project team	project program	previous projects feedback	stratigic brief	The project team
S0T1	Provide Business Case and other core project requirements and contribute to development of Strategic Brief as required	x					Client and/or client adviser
S0T2	Collate comments and facilitate workshops to discuss Business Case and develop Strategic Brief with project team members	x				x	Project lead- all the team members
S0T3	Discuss initial considerations for assembling the project team		x				Project lead
S0T4	Establish Project Programme			x			Project lead
S0T5	Collate Feedback from previous projects				x		Project lead
S0T6	Contribute to preparation of Strategic Brief					x	Lead designer
S0T7	Comment on project Programme			x			Lead designer
S0T8	Provide Feedback from previous projects				x		Lead designer
S0T9	Contribute to preparation of Strategic Brief					x	Architect
S0T10	Discuss project with appropriate planning authority					x	Architect
S0T11	Provide Feedback from previous projects				x		Architect
S0T12	Contribute to preparation of Strategic Brief					x	Building services engineer
S0T13	Contribute to preparation of Strategic Brief					x	Civil & structural engineer
S0T14	Contribute Cost Information to preparation of Strategic Brief					x	Cost consultant
S0T15	Contribute to preparation of Strategic Brief					x	all additional roles

Fig. 6.1 Interactions between the three aspects of the building design process in the strategic brief stage

6.2.2 Preparation and brief stage

In this stage, the core objective that is required to be established is the initial project brief, which includes several design process components such as the feasibility studies, site information, handover strategy, risk assessment, schedule of services, design responsibility matrix, and project execution plan. All these design process components build up the initial project brief as well as being part of the next design stage's outcome (Ostime 2013). The matrix in Fig. 6.2 indicates the design tasks that are assigned to the design team and the design activities that are the design tasks are establishing. The matrix in Fig. 6.2 indicates that the preparation and brief stage requires twenty-five design tasks to initialise and establishes 17 design process components, which are listed in the rows of the matrix below. In addition, eight design team members are required to accomplish these design tasks.

2	Preparation and Brief stage	assembling and monitoring the project team	project program	project objectives	quility objectives	sustainablety strategies	project budget	feasibility studies	Site information	Projects roles table	Constrectual tree	Handover strategy	Risk assessment	Schedule of services	Design responsibility matrix	Information exchange	Project Execution plan	Project roles
S1T1	Provide information for and contribute to contents of Project Execution Plan as required																x	All roles
S1T2	Contribute to development of Initial Project Brief including Project Objectives, Quality Objectives, Project Outcomes, Sustainability Aspirations, Project Budget and other parameters or constraints			x	x	x	x											Client and/or client adviser
S1T3	Develop Initial Project Brief with project team including Project Objectives, Quality Objectives, Project Outcomes, Sustainability Aspirations, Project Budget and other parameters or constraints			x	x	x	x											Project lead
S1T4	Collate comments and facilitate workshops as required to develop Initial Project Brief																	Project lead
S1T5	Prepare Project Roles Table and Contractual Tree and continue assembling and appointing project team members									x	x							Project lead
S1T6	Prepare Schedule of Services and develop Design Responsibility Matrix including Information Exchanges with lead designer													x	x	x		Project lead
S1T7	Review Project Programme and Feasibility Studies							x										Project lead
S1T8	Prepare Handover Strategy, Risk Assessments and Project Execution Plan											x	x				x	Project lead
S1T9	Monitor and review progress and performance of project team	x																Project lead
S1T10	Where required, Contribute to preparation of Initial Project Brief																	Lead designer
S1T11	Contribute to assembling of project team	x																Lead designer
S1T12	Contribute to preparation of Handover Strategy and Risk Assessments											x	x					Lead designer
S1T13	Comment on Project Programme		x															Lead designer
S1T14	Monitor and review progress and performance of design team	x																Lead designer
S1T15	Contribute to preparation of Initial Project Brief																	Architect
S1T16	Discuss project with appropriate planning authority																	Architect
S1T17	Undertake Feasibility Studies							x										Architect
S1T18	Prepare Site Information report								x									Architect
S1T19	Contribute to preparation of Initial Project Brief																	Building services engineer
S1T20	Contribute to Site Information report								x									Building services engineer
S1T21	Contribute to preparation of Initial Project Brief																	Civil & structural engineer
S1T22	Contribute to Site Information report								x									Civil & structural engineer
S1T23	Contribute to preparation of Initial Project Brief																	Cost consultant
S1T24	Prepare Project Budget in consultation with client						x											Cost consultant
S1T25	Where required, contribute to preparation of Initial Project Brief																	All additional project roles

Fig. 6.2 Interactions between the three aspects of the building design process in the preparation and brief design process stage

6.2.3 Concept design stage

In this stage, the core objectives that need to be established are the concept design outlines of the structural, architectural, and building services systems. In addition, several design process components are required to be established and developed: cost information, project strategies, and final project brief (Ostime 2013). The matrix in Fig. 6.3 indicates the design tasks that are assigned to the design team and the design components that the design tasks are establishing. The matrix in Fig. 6.3 indicates that the concept design stage requires 38 design tasks to initialise and establishes 20 design process components, which are listed in the rows of the matrix below. In addition, in this stage the roles of the health and safety engineer and the construction lead start by establishing the design tasks of the concept design stage.

3	Concept Design stage	Research and Development aspects	Construction Strategy	Health and Safety Strategy	Planning Application	Operational Strategy	Maintenance strategy	stage Design Programm	assembling and monitoring the project tea	project program	sustainablety strategies	Handover strategy	Risk assessment	Design responsibility matrix	Information exchange	Project Execution plan	Initial Project Brief	final project brief	project strategies	cost information	concept design	Project roles
S2T1	Contribute to Health & Safety Strategy as required			x																		All roles
S2T2	Provide information for and contribute to contents of Project Execution Plan as required															x						All roles
S2T3	Contribute to development of Final Project Brief																	x				All roles
S2T4	Comment on Concept Design proposals as they progress																				x	Client and/or client adviser
S2T5	Sign-off Concept Design and Final Project Brief																	x			x	Client and/or client adviser
S2T6	Comment on Project Strategies as requested																		x			Client and/or client adviser
S2T7	Monitor progress of Concept Design																				x	Project lead
S2T8	Collate and agree changes to the Initial Project Brief and issue Final Project Brief																x	x				Project lead
S2T9	Review Handover Strategy and Risk Assessments with project team											x	x									Project lead
S2T10	Review and update Project Execution Plan															x						Project lead
S2T11	Review Project Programme and agree any changes with project team								x	x												Project lead
S2T12	Comment on stage Design Programme and Cost Information							x												x		Project lead
S2T13	Monitor and review progress and performance of project team								x													Project lead
S2T14	Comment on design proposals and Project Strategies from design team members																		x		x	Lead designer- all team members
S2T15	Prepare Sustainability Strategy and Maintenance and Operational Strategy with input from project team as required					x	x				x											Lead designer- all team members
S2T16	Prepare stage Design Programme with input from other design team members																					Lead designer
S2T17	Comment on Cost Information																			x		Lead designer
S2T18	Monitor and review progress and performance of design team								x													Lead designer
S2T19	Prepare architectural Concept Design in accordance with the Initial Project Brief, Design Responsibility Matrix incorporating Information Exchanges and Design Programme									x				x	x		x				x	Architect
S2T20	Liaise with planning authorities as required																				x	Architect
S2T21	Submit Planning Application (stage 3 recommended)				x																	Architect
S2T22	Undertake third party consultations and any Research and Development aspects as required	x																				Architect
S2T23	Assist lead designer with preparation of stage Design Programme							x														Architect- lead designer
S2T24	Provide information for preparation of Cost Information and Project Strategies																		x	x		Architect
S2T25	Prepare Concept Design for building services design in accordance with the Initial Project Brief, Design Responsibility Matrix incorporating Information Exchanges and Design Programme									x				x	x		x				x	Building services engineer
S2T26	Undertake third party consultations as required and any Research and Development aspects	x																				Building services engineer
S2T27	Assist lead designer with preparation of stage Design Programme							x														Building services engineer- lead designer
S2T28	Provide information for preparation of Cost Information and Project Strategies																		x	x		Building services engineer
S2T29	Prepare Concept Design for structural design in accordance with the Initial Project Brief, Design Responsibility Matrix incorporating Information Exchanges and Design Programme									x				x	x		x				x	Civil & structural engineer
S2T30	Undertake third party consultations as required and any Research and Development aspects	x																				Civil & structural engineer
S2T31	Assist lead designer with preparation of stage Design Programme							x														Civil & structural engineer
S2T32	Provide information for preparation of Cost Information and Project Strategies																		x	x		Civil & structural engineer
S2T33	Prepare preliminary Cost information																			x		Cost consultant
S2T34	Assist lead designer with preparation of stage Design Programme							x														Cost consultant- lead designer
S2T35	Prepare Construction Strategy		x																			Construction lead
S2T36	Develop Health and Safety Strategy including statutory requirements			x																		Health & safety adviser
S2T37	Liaise with project Lead and lead designer as required																				x	additional project roles- project Lead -lead design
S2T38	Provide information as set out in the Design Responsibility Matrix incorporating Information Exchanges in accordance with Design Programme									x				x	x							All additional project roles

Fig. 6.3 Interactions between the three aspects of the building design process in the concept design process stage

6.2.4 Developed design stage

In this stage, the core objective mainly focuses on updating and developing the information from the concept design, which is an update of the architectural, structural, and building systems design as well as the cost information, and project strategy (Ostime 2013). The matrix in Fig. 6.4 indicates the design tasks that are assigned to the design team and the design components that the design tasks are establishing. The following matrix indicates that the developed design stage requires 37 design tasks to initialise and establishes 19 design process components, which are listed in the rows of the matrix below. In addition, the roles of this design stage are similar to the previous design stage.

4	Developed design stage	change control process	Research and Development aspects	Construction Strategy	Health and Safety Strategy	Planning Application	Operational Strategy	Maintenance strategy	stage Design Programm	assembling and monitoring the project team	project program	sustainablety strategies	Handover strategy	Risk assessment	Design responsibility matrix	Information exchange	Project Execution plan	project strategies	cost information	developed design	Project roles
S3T1	Contribute to Health & Safety Strategy as required				x																All roles
S3T2	Provide information for and contribute to contents of Project Execution Plan as required																x				All roles
S3T3	Comment on Developed Design proposals as they progress																			x	Client and/or client adviser
S3T4	Sign-off Developed Design																			x	Client and/or client adviser
S3T5	Comment on updated Project Strategies as requested																		x		Client and/or client adviser
S3T6	Monitor progress of developing design																			x	Project lead
S3T7	Review updated Handover Strategy and Risk Assessments with project team												x	x							Project lead- project team
S3T8	Review and update Project Execution Plan																x				Project lead
S3T9	Review Project Programme and agree any changes with project team									x	x										Project lead
S3T10	Comment on stage Design Programme and Cost Information								x												Project lead
S3T11	Manage Change Control process	x																			Project lead
S3T12	Monitor and review progress and performance of project team									x											Project lead
S3T13	Co-ordinate and comment on design proposals and Project Strategies as they progress																	x		x	Lead designer
S3T14	Update Sustainability Strategy and Maintenance and Operational Strategy with input from project team as required						x	x				x									Lead designer
S3T15	Prepare stage Design Programme in conjunction with other design team members								x												Lead designer- design team membe
S3T16	Comment on Cost Information																		x		Lead designer
S3T17	Monitor and review progress and performance of design team									x											Lead designer
S3T18	Prepare architectural Developed Design in accordance the Design Responsibility Matrix incorporating Information Exchanges, Design Programme and co-ordination comments from lead designer										x				x	x				x	Architect- lead designer
S3T19	Liaise with planning authorities as required																			x	Architect
S3T20	Submit Planning Application					x															Architect
S3T21	Undertake third party consultations as required and conclude any Research and Development aspects		x																		Architect
S3T22	Assist lead designer with preparation of stage Design Programme								x												Architect- lead designer
S3T23	Provide information for updated Cost Information and Project Strategies																	x	x		Architect
S3T24	Prepare building services Developed Design in accordance with the Design Responsibility Matrix incorporating Information Exchanges, Design Programme and co-ordination comments from lead designer										x				x	x				x	Building services engineer
S3T25	Undertake third party consultations and any Research and Development aspects as required		x																		Building services engineer
S3T26	Assist lead designer with preparation of stage Design Programme								x												Building services engineer
S3T27	Provide information for preparation of Cost Information and Project Strategies																	x	x		Building services engineer
S3T28	Prepare coordinated and updated proposals for structural design in accordance with the Design Responsibility Matrix incorporating Information Exchanges and Design Programme										x				x	x				x	Civil & structural engineer
S3T29	Undertake third party consultations as required and any Research and Development aspects		x																		Civil & structural engineer
S3T30	Assist lead designer with preparation of stage Design Programme								x												Civil & structural engineer- lead desi
S3T31	Provide information for preparation of Cost Information and Project Strategies																	x	x		Civil & structural engineer
S3T32	Update preliminary Cost information																		x		Cost consultant
S3T33	Assist lead designer with preparation of stage Design Programme								x												Cost consultant
S3T34	Update Construction Strategy			x																	Construction lead
S3T35	Update Health and Safety Strategy				x																Health & safety adviser
S3T36	Liaise with project Lead and lead designer as required																				All additional project roles
S3T37	Provide information as set out in the Design Responsibility Matrix incorporating Information Exchanges in accordance with Design Programme										x				x	x				x	All additional project roles

Fig. 6.4 Interactions between the three aspects of the building design process in the developed design process stage

6.2.5 Technical design stage

In this stage, the core objectives are to prepare the architectural, structural, and building service systems according to the design responsibility matrix, project strategies, and design programme. The matrix in Fig. 6.5 indicates the design tasks that are assigned to the design team and the design components that the design tasks are establishing. The matrix in Fig. 6.5 indicates that the technical design stage requires 38 design tasks to initialise and establishes 20 design process activities, which are listed in the rows of the matrix below. In addition, in this design stage the role of the contract administrator starts by establishing a design task.

5	Technical Design stage	Building Contract	change control process	Research and Development aspects	Construction Strategy	Health and Safety Strategy	Building Regulations Submissionn	Operational Strategy	Maintenance strategy	stage Design Programm	assembling and monitoring the project team	project program	sustainablety strategies	Handover strategy	Risk assessment	Design responsibility matrix	Information exchange	Project Execution plan	project strategies	cost information	Technical Design	Project roles
S4T1	Contribute to Health & Safety Strategy as required					x																All roles
S4T2	Provide information for and contribute to contents of Project Execution Plan as required																	x				All roles
S4T3	Comment on Technical Design proposals as requested																				x	Client and/or client adviser
S4T4	Comment on updated Project Strategies as requested																		x			Client and/or client adviser
S4T5	Monitor progress of developing design																				x	Project lead
S4T6	Review updated Handover Strategy, Project Strategies and Risk Assessments with project team													x	x				x			Project lead
S4T7	Review and update Project Execution Plan																	x				Project lead
S4T8	Comment on stage Design Programme									x												Project lead
S4T9	Manage Change Control process		x																			Project lead
S4T10	Monitor and review progress and performance of project team										x											Project lead
S4T11	Review Technical Design proposals and Project Strategies as they progress and integrate the design work specialist subcontractors in accordance with Design Programme											x									x	Lead designer
S4T12	Update Sustainability Strategy and Maintenance and Operational Strategy with input from project team as required							x	x				x									Lead designer
S4T13	Prepare stage Design Programme in conjunction with other design team members									x												Lead designer- design team members
S4T14	Monitor and review progress and performance of design team										x											Lead designer
S4T15	Liaise with specialist subcontractors as necessary																				x	Lead designer
S4T16	Prepare architectural Technical Design in accordance the Design Responsibility Matrix incorporating Information Exchanges, Design Programme and comments from lead designer											x				x	x				x	Architect
S4T17	Submit Building Regulations Submission (Building Warrant in Scotland)						x															Architect
S4T18	Undertake third party consultations as required and conclude any Research and Development aspects			x																		Architect
S4T19	Assist lead designer with preparation of stage Design Programme									x												Architect- Lead designer
S4T20	Provide information for update of Project Strategies																		x			Architect
S4T21	Liaise with specialist subcontractors as necessary																				x	Architect
S4T22	Prepare building services Technical Design in accordance with the Design Responsibility Matrix incorporating Information Exchanges, Design Programme and comments from lead designer											x				x	x				x	Building services engineer
S4T23	Undertake third party consultations as required and any Research and Development aspects			x																		Building services engineer
S4T24	Assist lead designer with preparation of stage Design Programme									x												Building services engineer- lead designer
S4T25	Provide information for update of Cost Information and Project Strategies																		x	x		Building services engineer
S4T26	Liaise with specialist subcontractors as necessary																				x	Building services engineer
S4T27	Prepare Technical Design for structural design in accordance with the Design Responsibility Matrix incorporating Information Exchanges and Design Programme											x				x	x				x	Civil & structural engineer
S4T28	Undertake third party consultations as required and any Research and Development aspects			x																		Civil & structural engineer
S4T29	Assist lead designer with preparation of stage Design Programme									x												Civil & structural engineer- lead designer
S4T30	Provide information for update of Cost Information and Project Strategies																		x	x		Civil & structural engineer
S4T31	Liaise with specialist subcontractors as necessary																				x	Civil & structural engineer
S4T32	Update preliminary Cost information																			x		Cost consultant
S4T33	Assist lead designer with preparation of stage Design Programme									x												Cost consultant
S4T34	Update Construction Strategy				x																	Construction lead
S4T35	Prepare Building Contract, agree with contractor and arrange completion																					Contract administrator
S4T36	Update Health and Safety Strategy					x																Health & safety adviser
S4T37	Liaise with project Lead and lead designer as required																				x	All additional project roles
S4T38	Provide information as set out in the Design Responsibility Matrix incorporating Information Exchanges in accordance with Design Programme											x				x	x				x	All additional project roles

Fig. 6.5 Interactions between the three aspects of the building design process in the technical design process stage

6.3. Descriptive analysis of the three aspects of the building design process based on the RIBA plan of work

This section of the research will provide a descriptive analysis of the three aspects of the building design process based on the RIBA plan of work. Those three aspects are the design tasks of each stage that are required to be established by the design team members, the design team members who are involved in the design process stages, and the design process components that are the outcomes of the design process tasks. Each of the three aspects consists of several connected aspects, such as a design task has to be accomplished by a design team member to establish a design process component or part of it.

6.3.1 Building design process tasks

According to Hamil (2013), the Multidisciplinary Schedules of Services of the RIBA plan of work ensure that all the design tasks required in the design stage are listed and determine who is required to establish each one. Therefore, this research will extract the design tasks of the design process stages based on the RIBA Multidisciplinary Schedules of Services provided in the RIBA toolbox with the list of the design team that are assigned to establish those design tasks. In addition, according to Ostime (2013), RIBA ranks the design tasks in eight categories in each stage of the building design process: core objectives, procurement, programming, town planning, suggested key support tasks, sustainability checkpoints, information exchange, and UK government information exchange. Tables 6.1, 6.2, 6.3, 6.4, and 6.5 in Appendix A-1 indicate the design tasks of each design process stage based on the Multidisciplinary Schedules of Services of the RIBA plan of work. In addition, the tables indicate the categories of design tasks that are indicated in the RIBA plan of work book (Ostime 2013); these categories are core objectives, procurement, programme, planning, suggested key support tasks, sustainability checkpoints, information exchange, and UK government information exchange. Appendix A-2 the RIBA plan of worktable, which includes the design tasks' categories and their location in the task categories.

6.3.2 Building design process team members

This section of the descriptive analysis identifies the design team members who are required to establish the design tasks in the RIBA plan of work. According to Ostime (2013), the RIBA guide for designing a building requires a number of roles. These roles are ranked in terms of their involvement in the building design process stages. Some project team members are required to work from the first building design process stage until the last stage, but others are only required to be involved in part of the design stages to accomplish a specific design task. In addition, according to the RIBA toolbox, two very significant questions regarding the building design process team are clearly answered, which are “Who is the project team?” and “What does the project team need to do?” The answer to the first question is found by listing the roles that are required for each stage of the building design process. Building a project roles table and contractual tree identifies the list. The project roles table consists of all the project roles that are required for the design stage, and the contractual tree identifies the contractual relationship between project parties. The second question is answered by assembling the two significant components of the building design process, which are design responsibility matrix and the schedule of the services, which will identify the responsibility of each member of the design team.

According to Ostime (2013), the building design process team comprises the client, client advisor, project lead, lead designer, architects, building services engineer, civil & structural engineer, cost consultant, construction lead, contract administrator, and health and safety advisor. Their involvement in the five stages of the RIBA plan of work differs, so this research will define each team member of the building design process, and will identify a design matrix that determines the stages where each design team member is involved in establishing a task in the design stage.

First, the client: the client is defined in the Oxford Dictionary as "a person or organization using the services of a professional person or company" (Oxford 2014). The client is the person who receives the design services from the project team. In some cases the client is the owner of the project and in other cases the client is someone who is authorised by the owner to receive the design services and interact with the project team. The client needs an advisor; the client advisor is an independent member of the design team who is responsible for monitoring and managing the building design process from the first design stages. Their task involves advising on the assembly of the project team as well as advising the client on how to enhance the efficiency of managing the project (Ostime 2013).

Second, the project lead: this is the project manager, whose responsibility is to control the project planning and designing, coordination between members of the design team, and financial control of the project (TARGETjobs 2014).

Third, the design lead: this role is mainly filled by an architect, although this is not always necessary because it depends on the project type; for example, in a high-serviced building, the services engineer might be the best person to be the design lead (CIOB 2014).

Fourth, the architect: this is the building designer; s/he has to work closely with the client and the building's users to ensure that the design of the building satisfies their needs in terms of functional requirements and financial requirements. In addition, architects are responsible for communicating with the design team to make sure that the other building systems design is progressing with the architectural design (prospects 2014).

Fifth, the building services engineer: her/his responsibility is to design and maintain the services that the building is designed to function for. These services are heating, cooling, lighting, power, lifts, escalator, health and safety, acoustics, and security. In addition, building services engineers are responsible for taking into consideration the significant aspects of sustainability in building systems to ensure an efficient building design (Engineer: 2014).

Sixth, the civil & structural engineer: these professionals are responsible for maintaining the building structure and designing its structural components. In addition, (engineer 2014), civil engineers are involved in the project design, development and construction. Their main job is to ensure that the project is constructed safely and on time, and that it enhances the quality of the users' lives.

Seventh, the cost consultant: according to the CIOB (2013), the cost consultant's the main job is to establish the cost planning, which evolves and changes during the life of the project. The cost consultant provides the client with details of the similarity of the cost of the project to other projects, compares cost options, determines the project budget, and prepares a cost report.

Eighth, the construction lead: according to Prospects (2014), the construction lead is the construction manager whose responsibility is to run the construction on the building site or part of the construction site. In addition, the building manager is responsible for cooperating with the architect, engineer, buyers, estimator, and surveyors before the construction work starts.

Ninth, the contract administrator: according to the CIOB (2014), the contract administrator is the individual responsible for managing the construction contact of the building. The contract administrator can be an architect or the lead consultant or cost consultant.

Tenth, the health and safety advisor: according to Prospects (2014), the health and safety advisor is responsible for the safety of the building users and the people who are working on it, and for applying the safety policies.

These design team members are responsible for cooperating with each other from the beginning of the building design process until the establishment of the work; however, some responsibilities are different from others. The following table indicates the five stages of the building design process based on the RIBA plan of work as well as the interactions of the design team members through the design stages. In addition, it indicates the number of tasks that each member is responsible for accomplishing in each stage of the design process.

Table 6.6 Design process stages and the number of tasks for each design team member

The roles	Stage 0 Number of design tasks	Stage 1 Number of design tasks	Stage 2 Number of design tasks	Stage 3 Number of design tasks	Stage 4 Number of design tasks
Client	**1**	**1**	**3**	**3**	**2**
Client advisor	**1**	**1**	**3**	**3**	**2**
Project lead	**4**	**7**	**7**	**7**	**6**
Lead designer	**3**	**5**	**5**	**5**	**5**
Architect	**3**	**4**	**6**	**6**	**6**
Building services engineer	**1**	**2**	**4**	**4**	**5**
Civil & structural engineer	**1**	**2**	**4**	**4**	**5**
Cost consultant	**1**	**2**	**2**	**2**	**2**
Construction lead	**No tasks required at this stage**	**No tasks required at this stage**	**1**	**1**	**1**
Contract administrator	**No tasks required at this stage**	**No tasks required at this stage**	**No tasks required at this stage**	**No tasks required at this stage**	**1**
Health & safety advisor	**No tasks required at this stage**	**No tasks required at this stage**	**1**	**1**	**1**

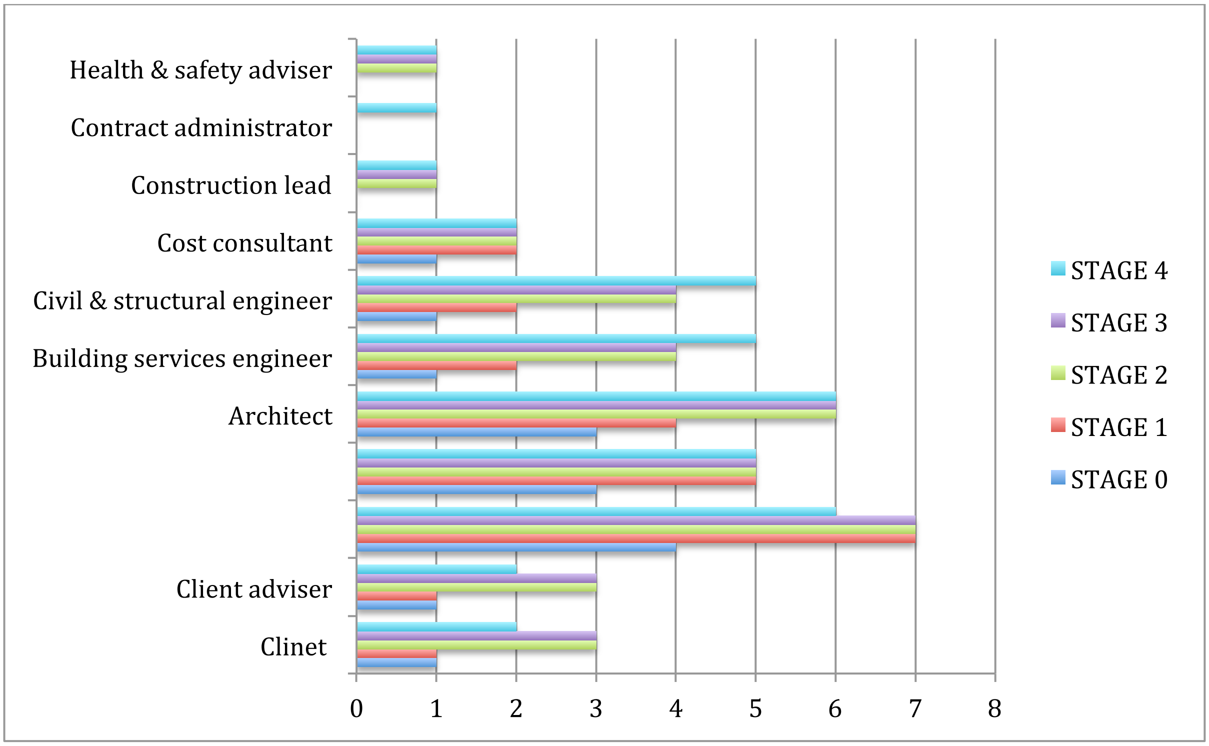


Fig. 6.6 Number of the design tasks for each design team member in each building design stage

The chart indicates that not all of the design team are involved in all of the building design process from the first stage to the last stage, such as the construction lead and the health and safety advisor; they begin their work in the building design process from the concept design stage to the developed design stage and the technical design stage. As another example, the contract administrator's involvement in the building design process is only in the technical design stage. The other design team members are involved in all of the building design stages, but their involvement varies from one stage to another; some design team members have to establish more tasks then others in the whole design process and in each design stage. The chart indicates that the project lead is the member of the design team with the most design tasks; her/his design tasks increase from four tasks in the strategic brief stage to seven tasks in the preparation and concept design, and developed design stages, and then decrease to six tasks in the technical design stage. As a result, the design team members' tasks generally increase as the design stages move forward, such as the lead designer, architect, building design services engineer, civil and structural engineer, and cost consultant's tasks. However, the project lead, and the client, and client advisor's design tasks increase from the first stages and decrease in the technical design stage.

6.3.3 Building design process components (outcomes)

The design process components are defined in this research in Chapter 4; they are the aspects of the building design process that is consider the outcomes of one or more of the design tasks that are established by one or more design team member(s). The components of the building design process in this research are identified from the RIBA plan of work and it is identified from investigation of the building design tasks. The components of the building design process are the business case, assembling and monitoring the project team, project programme, previous projects' feedback, strategic brief, project objectives, quality objectives, sustainability strategies, project budget, feasibility studies, site information, project roles table, contractual tree, handover strategy, risk assessment, schedule of services, design responsibility matrix, information exchange, project execution plan, initial project brief, research and development aspects, construction strategy, health and safety strategy, planning application, operational strategy, design programme stage, final project brief, project strategies, cost information, concept design, change control process, developed design, building contract, building regulations' submission ,and technical design. The following subsections will define these components in terms of their outcomes and their establishment.

6.3.3.1 Business case of a project

The business case of a project has to be established to determine why the project is needed and what specific benefits it will benefit specifically when it is accomplished (ProjectSmart 2014). In addition, business cases come in different forms such as a written document or a presentation that explains the usage of the resources, such as money for business needs. Moreover, according to Ostime (2013), the business case is an early component of the process, reflecting the needs of the project, and it needs to be established in order to move forward to the strategic definitions stage. According to the RIBA plan of work toolbox, the business case component of the design process is initialised in the strategic brief and finished before the stage is established.

6.3.3.2 Assembling and mentoring the project team

This component of the building design process is divided into two main aspects, which are assembling the design team, and monitoring the design team. Assembling the design team is initialised at the strategic brief stage and continues until the last stage of the building design process. As shown in the table, the design team is assembled in the strategic brief and remains until the last stage of the building design process. In addition, the chart indicates that some design team members are required to establish design tasks in the stages after the strategic design stage; this indicates that assembling a design team is a continuous process throughout the stages. Monitoring the design team is a task for the project lead, and it is a task that has to be repeated in each of the design process stages.

6.3.3.3 Project programme

One of the important components of the building design process is the project programme because it involves the establishment of a large number of design tasks and design team members. In addition, architectural programming has been defined as "the research and decision-making process that defines the problem to be solved by design" (Cherry 1999). Furthermore, Sanoff (1977) divided architectural programming process development into three phases: "problem identification", "information collection", and "information organization". In addition, Cherry (2009) described the process of architectural programming as consisting of six steps, which are project research, project goals, relevant information, determining strategies, quantitative requirements, and the programme summary. This indicates that the architectural programme is a very interactive design component in the building design process because its information content comprises the content of several design components as well as it is built up from the flow of information between design components.

Due to the significance of the architectural programme in the building design process, the RIBA plan of work has classified it as one of the task categories, which is programming tasks. According to Ostime (2010), the architectural programme is a design component that is initialised at the strategic brief stage and continues until the end of the building design process.

6.3.3.4 Previous projects' feedback

Receiving feedback from previous projects is a very significant component of the building design process because it enhances the problem-solving efficiency in the design. In this component, the project team is required to investigate and study similar projects in order to determine their advantages and disadvantages in relation to the current project. In addition, receiving previous projects' feedback significantly enhances the design of a project in terms of the main categories of design tasks that are required in the building design process stages.

6.3.3.5 Strategic brief

The strategic brief is the final outcome of the strategic definition brief. Generally, it is a combination of all the established results and information gathered at the strategic definition stage. According to Ostime (2013), a strategic brief has to include the client's objectives – what the client wants to achieve from the establishment of the project. These objectives are mainly related to functional requirements, environmental standards, level of quality, and lifespan. The strategic brief may include a statement of interest and more technical details. This design component is significantly important in establishing the next stage's component, which is the feasibility study. In addition, the strategic brief includes the business case for initialising the project.

6.3.3.6 Project objectives

Project objectives are the goals that need to be achieved in designing the building. According to ProjectSmart (2014), the clearer the project's objectives, the more achievable the project is. The project objectives are divided into three main aspects statement which brief of what are the goals of the project, measures, determining an assessment tool to measure the achievement of the objectives, and performance specification, which determines the value of successfully achieving each objective. In the RIBA plan of work, project objectives are a design component that needs to be established in the preparation and brief stage (Ostime 2013).

6.3.3.7 Quality objectives

Quality objectives are a design component that in some projects is part of the project objectives; however, the quality objectives in building design vary, and it is specifically the objectives of the project outcome. The quality of the project outcome has to be achieved in accordance with the design specification. In addition, the RIBA plan of work determines the project quality objectives component as a design component that required to be established in the preparation and brief stage.

6.3.3.8 Sustainability strategies

Sustainable buildings are structures that are environmentally efficient in terms of using resources during the building's life cycle, such as design, construction, operation, maintenance, renovation, and demolition. According to the RIBA plan of work, sustainability strategies are divided into eight checkpoints; each checkpoint is in a design stage. However, in this research there are five checkpoints during the design process, which are the design process sustainability checkpoints. Each sustainability checkpoint consists of a list that required to be checked by the design team in order to establish the design stage. This indicates that the sustainability strategy is a built up design process component that continues throughout the design process (Ostime 2013).

6.3.3.9 Project budget

The project budget has been defined as "The sum established by the owner as available for the entire project, including the construction budget, land costs, equipment costs, financing costs, compensation for professional services, contingency allowance, and other similar established or estimated costs" (Budget 2014). According to the RIBA plan of work, the project budget is a design process component that is initialised in the preparation and brief stage and finalised in the design concept.

6.3.3.10 Feasibility studies

The feasibility studies are the result of intensive research and investigation of a proposed project in terms of its potential value. The aim of a feasibility study is to uncover the strengths and the weaknesses of an existing project in terms of its future success. Put simply, the main criteria feasibility studies are investigating in a project are the cost of the project and the value of this cost that needs to be achieved. According to Ostime (2013), the RIBA plan of work feasibility studies component is a design process component that needs to be established in the preparation and brief stage.

6.3.3.11 Site information

Site information consists of several investigations of the project site, which means site analysis. According to Demkin (2001) site analysis is a significant building design process component because it involves a significant potential use of the site in relation to the architectural programme, environmental impact, impact on the surrounding community, and project budget. According to Ostime (2013), site information is analysed and gathered in the preparation and brief stage.

6.3.3.12 Project roles table

According to Hamil (2013), the project roles table shows the roles that are required for each stage of the building design process. In addition, using the project roles table spread sheet that is available in the RIBA toolbox helps to define the parties that are required to participate in the project through the building design process stages. Fig. 6.7 provides an example of a project roles table; it consists of a column that includes the building design team, and a row for each of the five design process stages. The empty spaces in the table should include the names of the parties that are involved in the building design process. The project roles table is a design process component that is initialised in the preparation and brief stage and finalised in the concept design stage.

Project Roles Table

	0 Strategic Definition	1 Preparation and Brief	2 Concept Design	3 Developed Design	4 Technical Design
Client					
Client adviser					
Project lead					
Lead designer					
Construction lead					
Architect					
Civil and structural engineer					
Building services engineer					
Cost consultant					
Contract administrator					
Health and safety adviser					
Access consultant					
Acoustic consultant					
Archaeologist					
BREEAM assessor					
Cladding specialist					
Catering consultant					
Facilities management (FM) adviser					
Fire engineer					
Highways consultant					
Information manager					
Interior designer					
Landscape architect					
Lighting designer					
Masterplanner					
Operational lead					
Party wall surveyor					
Planning consultants					
Security adviser					
Signage designer					
Sustainability adviser					
Technical adviser					

Fig. 6.7 Example of a project roles table according to Hamil (2013)

6.3.3.13 Contractual tree

The contractual tree is a design process component that is established after the project roles table has been completed. It determines contractual relations between the project roles (Hamil 2013). Fig. 6.8 provides an example of how the contractual tree of a project is required to be established. It indicates that the client is contracting with four parties, which are the RIBA client advisor, cost consultant, architectural practice, and project lead. In addition, it indicates that the architectural practice is contracting with the structural engineering practice and the building services practice. According to Ostime (2013), the contractual tree should be established in the preparation and brief stage of the building design process.

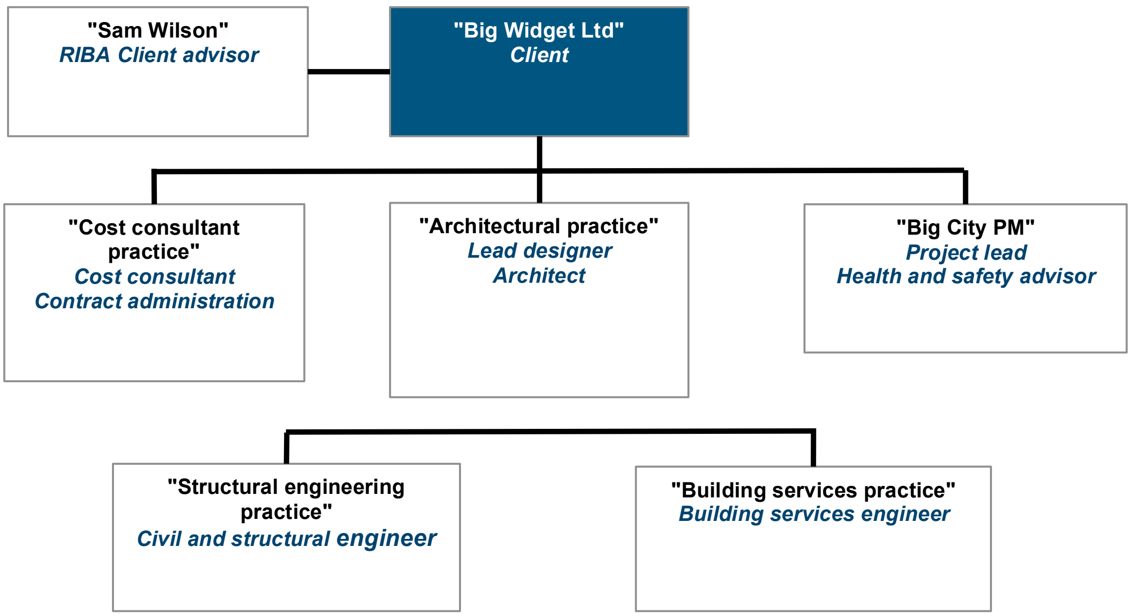


Fig. 6.8 Example of a contractual tree according to Hamil (2013)

6.3.3.14 Handover strategy

According to Ostime (2013), the handover strategy is a document that should include the phases of handover of the project, commissioning of the project, training of the project staff, and any requirements that will enhance the success of building occupation. The handover strategy is a design process component that required to be initiated in the preparation and brief stage, and continues to be developed through the building design process stages and finalised in the technical design stage.

6.3.3.15 Risk assessment

Risk assessment is a measurement of the risk that is related to a specific project; it can include qualitative or quantitative values. According to Ostime (2013), risk assessment is required to determine the risk for each project party. This design process component is initialised in the preparation and brief stage and continues to be developed through the design process to the technical design stage.

6.3.3.16 Schedule of services

The schedule of services is in the form of a table that ensures all the design tasks are set out and assigned to the design team that is required to establish them in accordance with the project roles table (Hamil 2013). In addition, the schedule of services, as shown in Fig. 6.9, is a table that consists of three columns: the first contains the project role; the second contains the name of the party in accordance with the project roles table; and the third contains the design tasks that are assigned to the roles. Each design stage has a schedule of services that determines that tasks required establishing the design process components. This design process component is established in the preparation and brief stage.

RIBA Plan of Work 2013

RIBA

Multidisciplinary Schedule of Services

0 - Strategic Definition

Project role	Party	Tasks to be undertaken
All roles		
Client and/or client adviser	0	Provide Business Case and other core project requirements and contribute to development of Strategic Brief as required
Project lead	0	Collate comments and facilitate workshops to discuss Business Case and develop Strategic Brief with project team members
		Discuss initial considerations for assembling the project team
		Establish Project Programme
		Collate Feedback from previous projects
Lead designer	0	Contribute to preparation of Strategic Brief
		Comment on project Programme
		Provide Feedback from previous projects
Architect	0	Contribute to preparation of Strategic Brief
		Discuss project with appropriate planning authority
		Provide Feedback from previous projects
Building services engineer	0	Contribute to preparation of Strategic Brief
Civil & structural engineer	0	Contribute to preparation of Strategic Brief
Cost consultant	0	Contribute Cost Information to preparation of Strategic Brief
Construction lead	0	N/A
Contract administrator	0	N/A
Health & safety adviser	0	
All additional project roles		Contribute to preparation of Strategic Brief

Fig. 6.9 Example of a schedule of services according to Hamil (2013)

6.3.3.17 Design responsibility matrix

The design responsibility matrix is a design process component that required to be initialised in the preparation and brief stage and finalised in the concept design stage. According to Hamil (2013), in the preparation and brief stage the design responsibility is defined, which provides a clear vision of what is to be delivered in terms of design aspects and from who and in which design stage. This leads to establishing the design responsibility matrix, which consists of a table, as shown in Fig. 6.10, that contains all the project design aspects, and the rows consist of the three design stages, which are the concept, developed, and technical design. Under each stage there are three columns, which consist of design responsibility, which indicates the party responsible for designing the design aspect, level of design, which indicates the type of design in terms of its detail, and information exchange, which indicates the type of information that is required.

		2 - Concept Design			3 - Developed Design			4- Technical Design		
Aspect of design		Design team			Design team			Design team		
Classification	Title	Design responsibility	Level of design	Information exchange	Design responsibility	Level of design	Information exchange	Design responsibility	Level of design	Information exchange
15-05	Substructure									
15-05-65	Piling									
15-65-75	Insitu concrete frame									
15-65-75	Post tensioned concrete frame									
15-65-75	Precast concrete frame									
15-65-75	Steel frame including secondary steel									
20-10-20	Suspended ceilings									
20-15-05	Hard landscaping									
20-25-75	Roof lights									
20-50-30	Flat roof systems									
20-50-50	Metal sheet roof systems									
20-55	Carpets and other floor finishes									
20-55-15	Screeds									
20-55-35	Internal floor tiling									
20-55-70	Raised access floors									
20-55-95	Timber flooring									
25-05-60	Panel cubicle systems									

Fig. 6.10 Example of a design responsibility matrix according to Hamil (2013)

6.3.3.18 Information exchange

The information exchange is a design process component that is initialised in the preparation and brief stage and continues to develop through the design process stages to the technical design. This component consists of all the information that needs to be carried out from one design stage to another.

6.3.3.19 Project execution plan

The project execution plan sets out a strategy to manage the project and describes the policies and procedures that will be adopted (CIO 2014). Ostime (2013) defined it as a mechanism that gives links to the specific requirements of a project. This design process component is a developed component that continues in the development from the preparation and brief stage to the technical design stage.

6.3.3.20 Initial project brief

The initial project brief is a design process component that is established in the preparation and brief stage and finalised in the concept design stage. According to Ostime (2010), the project brief is a document that includes all the technical information and design intentions and indicates how these requirements are going to be addressed. It is the result of the whole project teamwork of research and development. The project brief includes the feasibility studies, site information, research and functional needs, environmental impact consideration, constraints, cost information and other significant outcomes of the strategic and definitions stage, and preparation and brief stage.

6.3.3.21 Research and development aspects

Research and development aspects are a design process component that is initialised in the concept design and finalised in the developed design stage. This component considers the design of the building.

6.3.3.22 Construction strategy

The construction strategy is the consideration of the construction that is determined in the design process. It consists of the process of constructing the building. This building design component is initialised in the concept design and finalised in the developed design stage.

6.3.3.23 Health and safety strategy

The health and safety strategy is established to ensure the safety of the building and the workers on the construction site as well as the users of the building. This design process component is initialised in the concept design stage and finalised in the developed design stage.

6.3.3.24 Planning application

The planning application is the request for permission that has to be submitted after the design team fills in the application, and this request for permission is to allow a building to be built on a specific piece of land. This design process component required to be initialised in the concept design stage and finalised in the developed design process stage.

6.3.3.25 Operational strategy

The operational strategy is a plan of action that indicates how the building's resources will be utilised. It should include a plan of how the building will be operated and used in the future. This design process component is initialised in the concept design stage and finalised in the technical design stage.

6.3.3.26 Design stage programme

The design stage programme is the programme of the process that will be undertaken by the design team in the stage. This design component is initialised in the concept design stage and finalised in the technical design stage

6.3.3.27 Final project brief

The finial project brief is a design component that is established in the concept design stage; it is a document that includes all the information in the initial brief, which has been updated in the concept design and finalised.

6.3.3.28 Project strategies

The project strategies are a design process component that is initialised in the concept design stage and finalised in the technical design stage. This component consists of all the project strategies that have been developed though the building design process stages, such as fire and safety, maintenance, operational, and sustainability strategies (Ostime 2013).

6.3.3.29 Cost information

The cost information is a design process component that is carried out by the cost consultant; it analyses the cost of the buildings in other, similar projects and determines if the project budget is compatible with the requirements of the project. This design process component is initialised in the concept design stage and finalised in the technical design stage (Ostime 2013).

6.3.3.30 Concept design drawings

The concept design drawings include the outlines of the building design as well as the structural design, and the building services systems. This design process component is established in the concept design stage (Ostime 2013).

6.3.3.31 Change control process

The change control process is a design process component that required to be established in case of any change in the design process or in the information of the design team and design tasks that are assigned to the design team.

6.3.3.32 Developed design drawings

The developed design drawings include the updated and more developed and detailed outlines of the building design as well as the structural design, and the building services systems. This design process component is established in the developed design stage (Ostime 2013).

6.3.3.33 Building contract

The building contrast is a design process component that has to be established by the client and handed to the building contractor to construct the building.

6.3.3.34 Submission of building regulations

Submission of building regulations is an outcome of the design process that required to be established in order for the building to meet the regulations of the town or city and the government.

6.3.3.35 Technical design drawings

The technical design drawings include all the required architectural drawings, structural drawings and building services systems drawings in accordance with the design responsibility matrix, project strategies, and design programme. This design process component is established in the technical design stage (Ostime 2013).

6.3.4 Locating design process components in design process stages

This section of the research will indicate the location of each design process component through the whole design process as well as the stage in which it is initialised in and the stage in which it is finalised, using the design structure matrix that lists the design process components in one column and the stages of the building design process in five other columns, and the interactions of the design component with the design stage. Fig. 6.11 shows at which stage the design process components are established through the whole design process stages.

The design process component	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4
Business case	X				
Assembling and monitoring the project team		X	X	X	X
Project programme	X	X	X	X	X
Previous projects' feedback	X				
Strategic brief	X				
Project objectives		X			
Quality objectives		X			
Sustainability strategies		X	X	X	X
Project budget		X	X		
Feasibility studies		X			
Site information		X			
Projects roles table		X	X		
Contractual tree		X			
Handover strategy		X	X	X	X
Risk assessment		X	X	X	X
Schedule of services		X			

Design responsibility matrix		X	X	X	X
Information exchange		X	X	X	X
Project Execution plan		X	X	X	X
Initial Project Brief		X	X		
Research and Development aspects			X	X	
Construction Strategy			X	X	
Health and Safety Strategy			X	X	
Planning Application			X	X	
Operational Strategy			X	X	X
Stage Design Program			X	X	X
Final project brief			X		
Project strategies			X	X	X
Cost information			X	X	X
Concept design			X		
Change control process				X	X
Developed design				X	
Building Contract					X
Building Regulations Submission					X
Technical Design					X

Fig. 6.11 Design process stages in which the design process components are initialised and established

6.4 Uncovering the typological characteristic of the design process stages' information flow networks

This section of the research models the interactions and information flow of the three aspects of the building design process in the form of networks; each network will present a design stage based on the RIBA plan of work. The networks will include the interactions between the design tasks, design components, and design team. Each of the three aspects will be presented as a node in the network stage, and each edge of the network indicates information flow between connected nodes, such as a design team member is connected to the design tasks that s/he is required to establish in the design stage as well as the design activities that are established by the design tasks, and these activities are connected to the design tasks that establish it. The goal of modelling the information flow and propagation of the building design process is to investigate the building design process aspects' controllability and importance in terms of knowledge diffusion in a building design process. Therefore, the investigation will be established by modelling the design process networks using social network analysis software Gephi to uncover the typology of the building design process stages. Then social network analysis measures will be applied to the networks to identify the significance of knowledge diffusion in the design process stage.

6.4.1 Design process stage information flow network typologies

In this section of the research, the information flow networks of each design process stage will be presented based on the interaction of the design structure matrix of Fig. 6.1, 6.2, 6.3, 6.4, and 6.5 generated for each design stage, which indicate the flow of information between the design tasks, design team, and design process components in the strategic definitions, preparation and brief, concept design, developed design, and technical design stage.

6.4.1.1 Information flow network at the strategic definitions stage

The network shown in Fig. 6.12, which was modelled by using Gephi, is the strategic definitions stage network, which consists of 52 nodes and 82 edges. The nodes represent the three aspects of the building design process, which are the design tasks, design process components, and design team members. The larger the node, the higher the degree centrality results. This indicates that a node has a significant role in the information flow in the network. In this network, the strategic definition stage network is contracted around two larger nodes with a higher centrality degree in the network, the strategic brief components and the project lead design team member. Most of the design tasks and design activities are connected to the strategic brief, which results in a degree centrality of 14 because it is the main design process component that needs to be established in this design stage. In addition, the project lead has a degree centrality of 9; this indicates an important centrality for the project lead in this design stage, as also shown in the diagram.

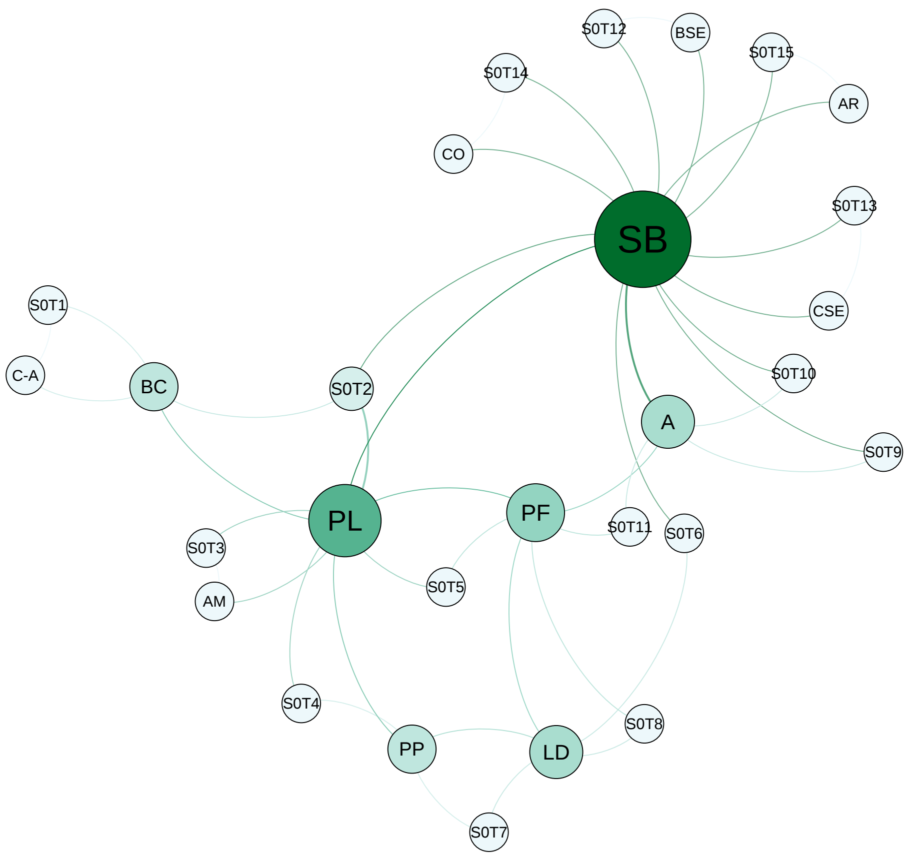


Fig. 6.12 Typology of the strategic definitions stage information flow network

6.4.1.2 Information flow network of the preparation and brief stage

The network shown in Fig. 6.13 indicates the preparation and brief stage network, which consists of 49 nodes and 100 edges. In this network, the preparation and brief stage network is centred on three larger nodes with a higher centrality degree in the network, which are the initial project brief design process component with a degree of 18, the project lead with a degree centrality of 22, and lead designer with a degree centrality of 10. This indicates the preparation and brief stage is mainly focused on establishing the initial project brief and the most significant roles that are involved in the establishment of this design process component are the project lead and the lead designer.

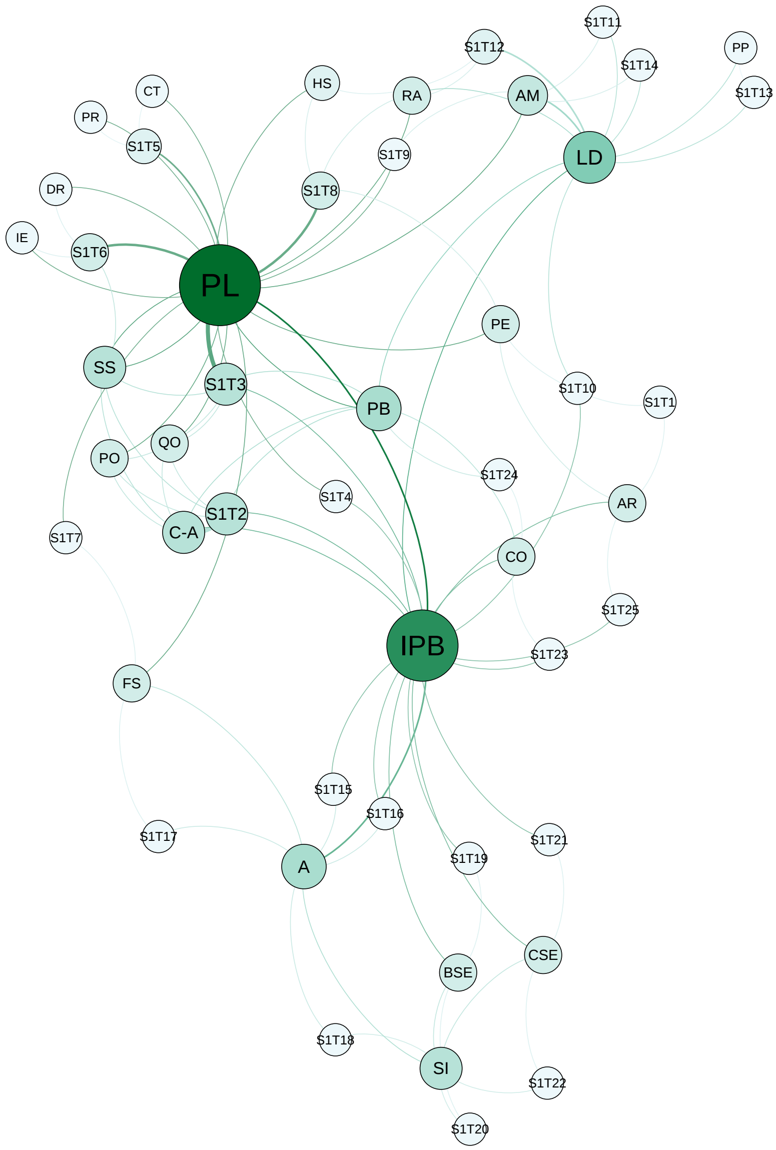


Fig. 6.13 Typology of the preparation and brief stage information flow network

6.4.1.3 Information flow network of the concept design stage

The network shown in Fig. 6.14 indicates the concept design stage network, which consists of 66 nodes and 159 edges. In this network, the concept design stage network, five significant nodes are playing very important roles in terms of knowledge diffusion to establish the concept design. They are the project lead with a degree centrality of 18, the architect with degree centrality of 16, the civil and structural engineer with a degree of 14, and building services engineer with degree of 13. In this stage, the role of the architect has been increased due to the need to establish the concept design component, which has resulted in a 17-degree centrality.

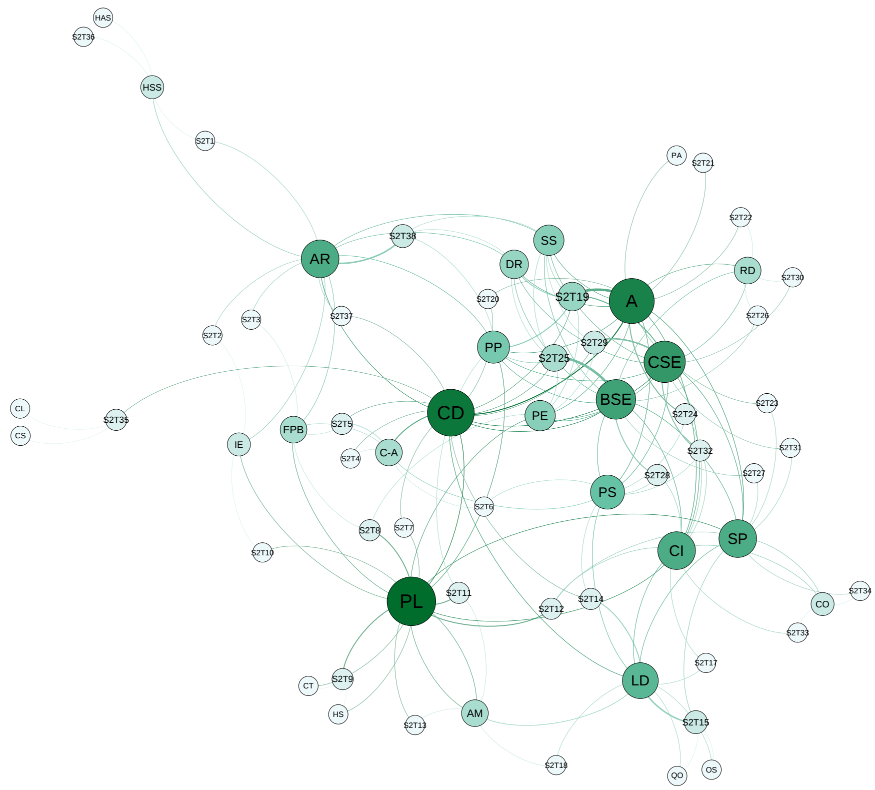


Fig. 6.14 Typology of the concept design stage information flow network

6.4.1.4 Information flow network of the developed design stage

The network shown in Fig. 6.15 indicates the developed design stage network that consists of 64 nodes and 146 edges. In this network, the important design process component is the developed design component of the design process with a degree centrality of 19. In addition, the significant roles in terms of knowledge diffusion in the developed design stage are the project lead with a degree centrality of 16 and the architect with a degree centrality of 14.

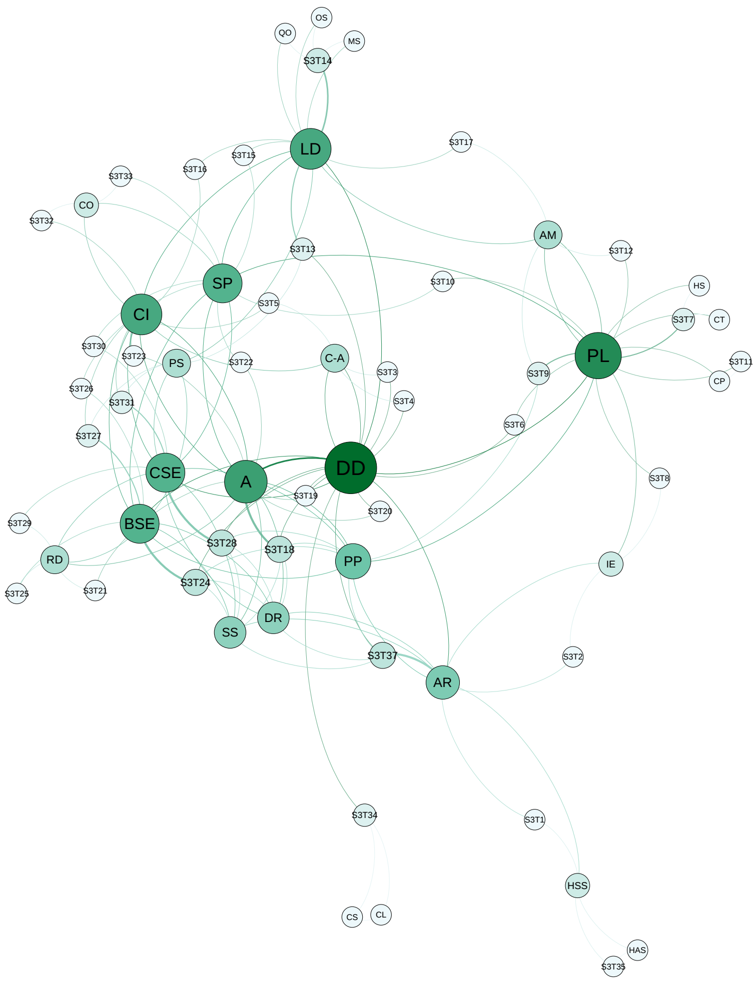


Fig. 6.15 Typology of the developed design stage information flow network

6.4.1.5 Information flow network of the technical design stage

The network shown in Fig. 6.16 indicates the technical design stage network has 66 nodes and 146 edges, and consists of several important nodes that are significant in terms of spreading knowledge in this stage. These nodes are the ones with the higher degree centrality in this network, which are the lead designer with a degree centrality of 15, the architect, who also has degree centrality of 15, and the project lead with a degree centrality of 14. The most significant component of the design process in this stage is the technical design component with a 21-degree centrality.

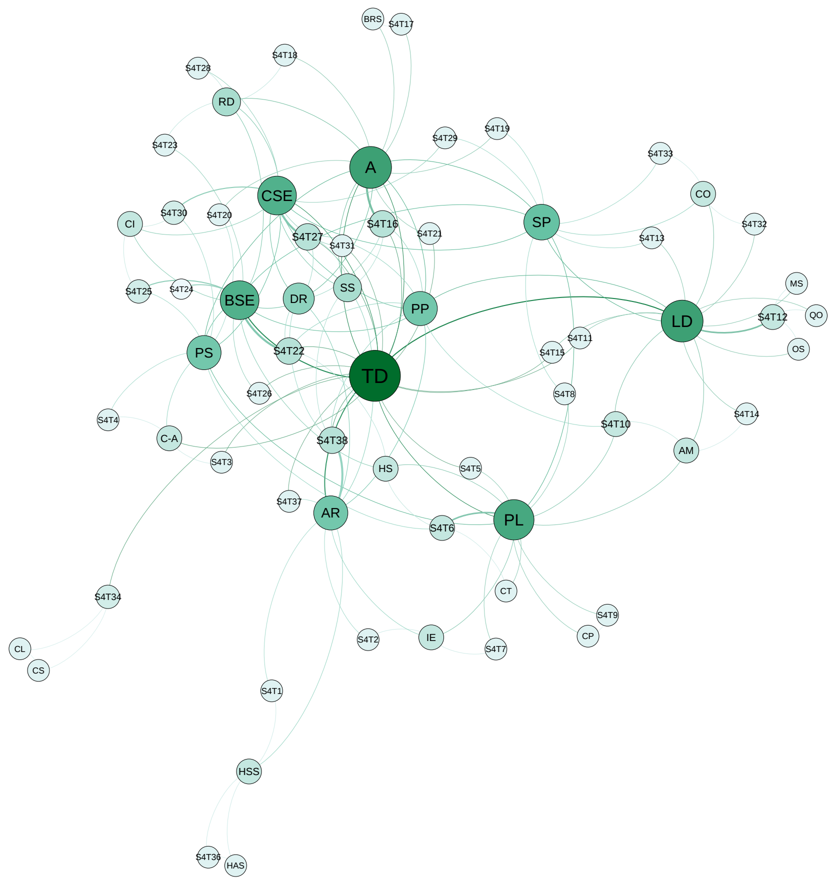


Fig. 6.16 Typology of the technical design stage information flow network

6.4.2 Network centrality measures of the buildings design process aspects

One of the significant aspects when analysing networks are the centrality measures because they determine the most important nodes in the networks in terms of the information flow diffusion of knowledge and the ability of those nodes to spread information and knowledge though the network. In this research, the use of centrality measures will significantly enhance the ability to uncover the complex flow of information in building design process stages and assess the knowledge diffusion controllability aspects in the building design process. The centrality measures that are going to be calculated using Gephi are the degree centrality, closeness centrality, and betweenness centrality. The following subsection explains the definitions of the centrality measures that are going to be used in this research as well as the interpretation of these measures to the information flow and diffusion of knowledge in the design process stages' networks.

6.4.2.1 Degree centrality of design process aspects

This is defined as the number of edges that are connected to a node in a network. The measure of degree centrality shows the number of edges that are connected to a design team member in the building design process, which indicates the number of times that the design team member has received information about a design task and delivered information about a design process component. This measurement indicates the activities of the design team member in the design process by establishing a design task and participating in or establishing a design process component. In addition, the degree centrality measure indicates the number of edges that are connected to the design components. This indicates the number of times the design process component is connected to design tasks that are required to establish it and the times that this component is connected to a design team member who needs to participate in or establish it. This measurement indicates the activities, either a design task or design team member's participation that are required to be carried out in order to establish a design process component.

This research will quantify the degree centrality of the design team members and the design process components in order to quantify the number of interactions that work as a channel to pass information from and to the nodes of design team members and design process components. Table 6.7 indicates the interpretations of the degree centrality to the three aspects of the building design process.

Table.6.7 Interpretation of the degree centrality in terms of information flow and knowledge diffusion of the three aspects of the building design process

The node in the network	The interpretation of the degree centrality in terms of knowledge diffusion in a design stage
Design process tasks	The degree centrality of the design task indicates the paths of information that flow from the design task to the design team and to the design process component that the design task is part of establishing
Design team member	The degree centrality of the design team member indicates the number of design tasks that has to establish and the number of design process components that s/he is involved in establishing.
Design process component	The degree centrality of the design process component indicates the number of design tasks that required to be established, as well as the number of times that the design team member contributes to this.

6.4.2.2 Closeness centrality of design process aspects

The closeness centrality of a node measures its centrality in the design stage network. Closeness centrality measures the average distance of a node to all nodes in the network and the more central the node in the network, the lower its distance to all other nodes in the network. It indicates the ability information to spread from one node to other nodes.

The closeness centrality quantifies the indirect paths that connect nodes to each other to identify their closeness centrality to all nodes. The measure of closeness centrality indicates the average path distance of the design team member and design process component to all nodes in the design stage network. This measurement indicates the importance of a design team member in passing information to the design process components by establishing her/his tasks. In addition, it indicates the closeness of a design process component to the entire network of the design stage, which determines its importance in the design stage network. This research will quantify the closeness centrality of the design team members and the design process components in order to determine the centrality of each design team member and design process component in the networks of the stage to indicate the significance of the design team member in passing information through the stage network as well as the significance of the design process component in the design process stage. Table 6.8 indicates the interpretations of the degree centrality of the three aspects of the building design process.

Table.6.8 Interpretation of the closeness centrality in terms of information flow and knowledge diffusion of the building design process aspects

The node in the network	The interpretation of the closeness centrality in terms of knowledge diffusion in a design stage
Design process tasks	The closeness centrality of the design task indicates the average distance of the design task to all nodes in the network. It indicates how central the design task is, which indicates its importance in terms of knowledge diffusion in the network.
Design team member	The closeness centrality of the design team member indicates the average distance of the design team member to all nodes in the network. It indicates how central the design team member is in the design stage, which can indicate the importance of the design team member in terms of knowledge diffusion in a stage network.
Design process component	The closeness centrality of the design process component indicates the average distance of the design process components to all nodes in the network. It indicates how central the design process components are in the design stage, which can indicate the importance of the design process component in terms of knowledge diffusion in a stage network.

6.4.2.3 Betweenness centrality of design process aspects

Betweenness centrality measures the centrality of a node in connecting other nodes in networks. It measures how often the node is positioned in the shortest path between two nodes in a network. Betweenness centrality quantifies the number of times a node acts as a bridge to connect two nodes through the shortest path between them. This measurement indicates the importance of the nodes in the network in terms of passing the information through the network. The node with a higher value of betweenness centrality in a network is the most important node in the network information flow.

The measurement of betweenness centrality indicates the number of times that the design team member has passed on information to establish a design process component as well as indicating the number of times that the design process component acts as a bridge to connect information flow between the design team members. This research will quantify the betweenness centrality of the design team members and the design process components in order to determine the importance of the design team members in terms of information flow in the design stage network as well as the importance of the design process component in terms of information flow compared to other design components in the stage networks. Table 6.9 indicates the interpretations of betweenness centrality of the three aspects of the building design process.

Table 6.9 Interpretations of the betweenness centrality of the three aspects of the building design process.

The node in the network	The interpretation of the betweenness centrality in terms of knowledge diffusion in a design stage
Design process tasks	The betweenness centrality of the design task indicates the number of times the design tasks works as a bridge to pass information through two nodes in the network. The betweenness centrality indicates the importance of the design tasks in terms of spreading information in the network.
Design team member	The betweenness centrality of the design team member indicates the number of times the design team member works as a bridge to pass information through two nodes in the network. The betweenness centrality indicates the importance of the design team member in terms of spreading information in the network.
Design process component	The betweenness centrality of the design process component indicates the number of times the design component acts as a bridge to pass information between two nodes in the stage network. It indicates the importance of the node in terms of knowledge diffusion in the network.

6.5. General characteristics of the network centrality measures of the building design process stages

The general structural characteristics of the networks of the building design process stages measure the three main centrality measures of the design process information flow network nodes. The tables below indicate the means, standard deviation, sum, variance and the minimum and maximum of the centrality measures for each stage. In addition, the results of the centrality measures were calculated by Gephi and exported to SPSS to calculate the means, standard deviation, sum, variance and the minimum and maximum of the centrality measures for each stage. The following subsections will provide the results for the centrality measures of all the design process stages. The results are calculated from all the nodes in the stages' networks including the three aspects, design team, design tasks, and design process components.

6.5.1 General characteristics of degree centrality

Table 6.10 indicates the general characteristics of the degree centrality results for the nodes of each stage in the building design process. It indicates that the higher mean results of degree centrality are for the concept design with an average of 4.82 edges per node in the network. This indicates that each node passes information through the concept design stage network 4.82 times. However, the number decreases as the design process moves forward. This indicates that the concept design stage is the peak of information and knowledge diffusion in the building design process. In addition, the standard deviation of the nodes' degree centrality in the design process stages resulted in a similar pattern to the mean with a higher result in the concept design stage of 4.20 and a lower result of 2.7 for the strategic divination stage. The standard deviation indicates that there is a larger gap between the numbers of interactions of the nodes in the concept design stage than in the other design stages. This indicates that there are significant nodes that influence the flow of information in the design stage more than in the other design stages, as well as their involvement in passing information through the design stage is higher than the nodes in the other stages. Moreover, the sum result indicates how big the network is; as the number of nodes increases, the possibility of interactions increases, so the sum result increases. In addition, the minimum interaction of the node in the networks are similar, which is two; this is because each design task is connected to the design process component that establishes a part of it and to the design team member that establishes it.

Table 6.10 Calculation of the degree centrality general characteristic using SPSS

	DEGRE				
	Strategic brief	**Preparation and brief**	**Concept design**	**Developed design**	**Technical design**
MEANS	**3.21**	**4.08**	**4.82**	**4.56**	**4.42**
SD	**2.7**	**3.8**	**4.20**	**4.09**	**4.15**
SUM	**90**	**200**	**318**	**292**	**292**
VAR	**7.21**	**14.45**	**17.65**	**16.79**	**17.2**
MIN	**2**	**2**	**2**	**2**	**1**
MAX	**14**	**22**	**18**	**19**	**21**

6.5.2 General characteristics of closeness centrality

Closeness centrality measures the distance of a node to all nodes in the network and the more central the node, the lower its closeness result. This measure indicates how well connected the network of the design stages the higher the average of the nodes closeness result the higher the distance between the nodes. Table 6.11 indicates the average closeness result of the nodes of the design stages networks. The technical design stage resulted in a higher average distance between the nodes in its networks with an average closeness of 2.63; however, the strategic definitions and the concept design resulted in lower averages of closeness of their nodes to each other with a result of 1.27 for the strategic definition stage and 2.07 for the concept design stage. In addition, the standard deviation measures the gap in closeness between the nodes in the networks and indicates that the preparation and brief stage scored the higher result with 1.22 standard deviation. This result indicates that the preparation and brief stage has several nodes that are scoring a high result for closeness, which indicates that there are verities between the tasks that are required to be established in this design stage. Thus, the number of standard deviations between the set of closeness results of the preparation and brief stage increases. Moreover, the maximum resulted node in terms of its closeness is the technical design stage with a node that resulted in 4.27.

Table 6.11 Calculation of the closeness centrality general characteristic using SPSS

	CLOSENESS				
	Strategic brief	**Preparation and brief**	**Concept design**	**Developed design**	**Technical design**
MEANS	**1.27**	**2.22**	**2.07**	**2.53**	**2.63**
SD	**0.65**	**1.22**	**1.15**	**1.21**	**0.97**
SUM	**35.54**	**109.03**	**137**	**161.9**	**173.84**
VAR	**0.42**	**1.49**	**1.32**	**1.48**	**0.95**
MIN	**0**	**0**	**0**	**0**	**0**
MAX	**2.56**	**4.62**	**4**	**4.5**	**4.27**

6.5.3 General characteristic of betweenness centrality

Betweenness centrality measures the number of times a node acts as a bridge to connect other nodes. In the table below the results indicate that the average time that nodes act as a bridge is in the higher level in the developed design stage with average betweenness centrality of 41.34 compared to the lower result of average betweenness, which is 2.4 for the strategic definitions stage. The increase of the average betweenness centrality indicates that the network's nodes are more central in the developed design stage than in the other design process stages. In addition, the results for betweenness of the nodes in the design stages vary in terms of their standard deviation; the higher standard deviation score occurs in the developed design stage. However, in terms of a maximum node betweenness centrality, the technical design stage resulted in a node with 347.83 betweenness centrality.

Table 6.12 Calculation of the closeness centrality general characteristic using SPSS

	BETWEENNESS				
	Strategic brief	**Preparation and brief**	**Concept design**	**Developed design**	**Technical design**
MEANS	**2.4**	**18.77**	**23.45**	**41.34**	**30.84**
SD	**6.38**	**57.9**	**59.42**	**89.97**	**75.66**
SUM	**67**	**920**	**1548**	**2646**	**2036**
VAR	**40.5**	**3360.5**	**3531.2**	**8096**	**5725.27**
MIN	**0**	**0**	**0**	**0**	**0**
MAX	**28.5**	**303**	**329.36**	**327.5**	**347.83**

6.6. Centrality measures of the three aspects of building design: process tasks, team, and process components

This section of the research will present the centrality measures of the design team members, design tasks, and design process components in each design process stage. In addition, it will compare the results for each design team member in each design process stage as well as it indicating the changes in the results of the design process components through the design process stages.

6.6.1. Centrality measures of the design tasks

Table 6.13 indicates that the design tasks' centrality measures are the same for each design task, which is 2 degrees of centrality, because each design task of the design process stage is connected to two sources of information flow, which are the design team member who is establishing the design task, and the design process component that the design task is establishing part of. However, the closeness centrality results are different for each design task because each design task is located differently in the network of its design stage. Therefore, this section of the research will present the results of the variety in closeness centrality for each design task of the design process stages and indicate the significant design tasks that are the most central in the network of the design stage.

Table 6.15 displays the results of the closeness centralities of the design tasks of the strategic definitions stage. The results indicate that the lower closeness centrality resulted 1 closeness centrality, which are the results of S0T1, S0T8, and S0T15 design tasks. These design tasks are the most central ones, those considered the most important design tasks in terms of knowledge diffusion in the strategic definitions stage. The next section of this chapter will assess the controllability of knowledge diffusion for these design tasks.

Table 6.13 Closeness centralities of the design tasks of the strategic definitions stage

The strategic definitions stage			
Design tasks	Closeness Centrality	Design tasks	Closeness Centrality
S0T1	1	S0T9	1.5
S0T2	1.57	S0T10	1.5
S0T3	2	S0T11	1.75
S0T4	2	S0T12	1.33
S0T5	2	S0T13	1.33
S0T6	1.5	S0T14	1.33
S0T7	2.56	S0T15	1
S0T8	1		

Table 6.14 displays the results of the closeness centralities of the design tasks of the preparation and brief stage. The results indicate that the lower closeness centrality resulted 1 closeness centrality, which are the results of S1T13 and S1T17 design tasks. These design tasks are the most central ones, those considered the most important design tasks in terms of knowledge diffusion in the preparation and brief stage. The next section of this chapter will assess the controllability of knowledge diffusion for these design tasks.

Table 6.14 Closeness centralities of the design tasks of the preparation and brief stage

Nodes	Closeness Centrality	Nodes	Closeness Centrality
S1T1	2.85	S1T14	3
S1T2	1.87	S1T15	3.46
S1T3	1.64	S1T16	3.46
S1T4	1.92	S1T17	1
S1T5	2.2	S1T18	4.63
S1T6	2.14	S1T19	3.36
S1T7	2.23	S1T20	3.88
S1T8	1.93	S1T21	3.36
S1T9	2.21	S1T22	3.88
S1T10	3.46	S1T23	3.46
S1T11	3	S1T24	2.86
S1T12	2.86	S1T25	2.85
S1T13	1		

Table 6.15 displays the results of the closeness centralities of the design tasks of the concept design stage. The results indicate that the lower closeness centrality resulted 1 closeness centrality, which are the results of S2T34 and S2T36 design tasks. Theses design tasks are the most central ones, those considered the most important design tasks in terms of knowledge diffusion in the concept design stage. The next section of this

chapter will assess the controllability of knowledge diffusion for these design tasks.

Table 6.15 Closeness centralities of the design tasks of the concept design stage.

Design tasks	Closeness Centrality	Design tasks	Closeness Centrality
S2T1	2.94	S2T21	2.7
S2T2	2.94	S2T22	2.65
S2T3	2.81	S2T23	2.65
S2T4	2.69	S2T24	2.26
S2T5	2.56	S2T25	2.29
S2T6	3.1	S2T26	2.76
S2T7	2.25	S2T27	2.86
S2T8	2.81	S2T28	2.29
S2T9	3.25	S2T29	2.33
S2T10	3.31	S2T30	2.71
S2T11	3	S2T31	2.76
S2T12	3.12	S2T32	2.29
S2T13	3.31	S2T33	4
S2T14	2.42	S2T34	1
S2T15	2.96	S2T35	2.67
S2T17	2.79	S2T36	1
S2T18	2.83	S2T37	2.38
S2T19	2.09	S2T38	2.38
S2T20	2.35		

Table 6.16 displays the results of the closeness centralities of the design tasks of the developed design stage. The results indicate that the lower closeness centrality resulted closeness centrality, which are the results of S3T22 with 1 closeness centrality, and S3T35 with 2.52 closeness centrality. These design tasks are the most central ones, those considered the most important design tasks in terms of knowledge diffusion in the developed design stage. The next section of this chapter will assess the controllability of knowledge diffusion for these design tasks.

Table 6.16 Closeness centralities of the design tasks of the developed design stage

Design tasks	Closeness Centrality	Design tasks	Closeness Centrality
S3T1	4.44	S3T19	2.76
S3T2	4.44	S3T20	2.76
S3T3	3.56	S3T21	2.92
S3T4	3.56	S3T22	2.52
S3T5	3.16	S3T23	2.76
S3T6	2.8	S3T24	2.64
S3T7	3.12	S3T25	2.96
S3T8	3.16	S3T26	2.56
S3T9	2.6	S3T27	2.68
S3T10	2.68	S3T28	2.88
S3T11	3.16	S3T29	3.64
S3T12	2.96	S3T30	2.76
S3T13	2.92	S3T31	3
S3T14	3.64	S3T32	3.12
S3T15	2.76	S3T33	3.12
S3T16	3	S3T34	3.96
S3T17	3	S3T35	1
S3T18	2.6	S3T37	3.12

Table 6.17 displays the results of the closeness centralities of the design tasks of the technical design stage. The results indicate that the lower closeness centrality resulted, which are the results of S4T36 with 1 closeness centrality, and S4T22 with 2.05 closeness centrality. These design tasks are the most central ones, which are considered the most important design tasks in terms of knowledge diffusion in the technical design stage. The next section of this chapter will assess the controllability of knowledge diffusion for these design tasks.

Table 6.17 Closeness centralities of the design tasks of the technical design stage

Design tasks	Closeness Centrality	Design tasks	Closeness Centrality
S4T1	3.67	S4T20	2.78
S4T2	3.44	S4T21	2.61
S4T3	3.06	S4T22	2.05
S4T4	3.44	S4T23	3.16
S4T5	2.5	S4T24	4.28
S4T6	2.58	S4T25	3.17
S4T7	3	S4T26	2.78
S4T8	2.78	S4T27	2.37
S4T9	3.05	S4T28	3.05
S4T10	2.11	S4T29	2.94
S4T11	2.72	S4T30	3.06
S4T12	3.6	S4T31	2.89
S4T13	3.11	S4T32	3.79
S4T14	3.22	S4T33	3.16
S4T15	2.72	S4T34	2.95
S4T16	2.26	S4T36	1
S4T17	2.95	S4T37	2.83
S4T18	2.74	S4T38	2.42
S4T19	2.67		

6.6.2 Centrality measures of the design team members

6.6.2.1 Degree centrality of design team

Table 6.18 contains the results of the design team degree centrality in each design process stage. The results indicate that the building design team results vary from one design stage to another in terms of their degree centrality and the number of interactions with other nodes, which indicates that information, passes through. The table indicates that the additional roles node resulted in a degree centrality of 12 in the concept design stage, which is the highest result for the additional roles in the design process stages. In addition, the highest involvement of knowledge diffusion for the client and client advisor in the design process stages is in the preparation and brief stage, concept design stage, and developed design stage with a degree centrality of 6. Moreover, the project lead result for degree centrality indicates that the project lead is connected to 22 nodes in the preparation and brief stage, which makes it the highest stage result for the project lead. The lead design degree centrality increases as the design process moves forward, with a higher result – a 15-degree centrality in the technical design stage. The architect resulted in a 16-degree centrality in the concept design with a heist degree centrality in the design process stages. The degree centrality of the civil and structural engineer, building services engineer, and cost consultant increases as the process moves forward. However, the construction lead and health and safety advisor remain the same in the design stages, as they required establishing design tasks. The next section of this chapter will assess the controllability of knowledge diffusion of those design team members with higher degree centrality results in each design stage.

Table 6.18 Degree centrality of all the design team members in each stage of the building design process

	DEGREE				
Design team	**Strategic brief**	**Preparation and brief**	**Concept design**	**Developed design**	**Technical design**
All additional roles	2	4	**12**	9	10
Client and client advisor	2	**6**	**6**	**6**	4
Project lead	9	22	18	16	14
Lead designer	5	10	11	13	15
Architect	5	7	16	14	15
Civil and structural engineer	2	4	13	12	13
Building services engineer	2	4	14	12	13
Cost consultant	2	4	4	4	4
Construction lead	**X**	**X**	2	2	2
Health and safety advisor	**X**	**X**	2	2	2

6.6.2.2 Closeness centrality of design team

The closeness centrality of the design team in the design process is calculated using Gephi. The closeness centrality of the design team varies from one stage to another, which indicates that design team members change their locations in the stage design network in each design stage. The results in the table below indicate that the additional roles category has a lower than average path to all nodes in the network in the concept design stage, which indicates that their centrality is greatest in the concept design stage. In addition, the client and the client advisor resulted in 1.9 closeness centrality in the preparation and brief stage, which indicates that they are more central to all nodes in this stage than in other design stages. In addition, the closeness centrality of the project lead is 2.55 in the concept design, which indicates that the project lead has a lower centrality in this design stage; however, in the role has a higher level of centrality in the strategic definitions stage. The next section of this chapter will assess the controllability of knowledge diffusion of those design team members with lower closeness centrality results in each design stage.

Table 6.19 Closeness centrality of all the design team members in each stage of the building design process

	Closeness				
Design team	**Strategic brief**	**Preparation and brief**	**Concept design**	**Developed design**	**Technical design**
All additional roles	0	3	**2.13**	3.625	2.88
Client and client advisor	0	**1.92**	2.8	3.04	3.58
Project lead	**1.33**	1.5	2.53	2.29	2.29
Lead designer	**1**	0	2.21	2.87	3.18
Architect	**1.33**	0	1.82	2.13	2.18
Civil and structural engineer	**1.5**	3.54	2.05	2.20	2.88
Building services engineer	**1.5**	3.54	1.95	2.875	3.47
Cost consultant	**1.5**	0	0	3.20	3.11
Construction lead	X	X	1	1	1
Health and safety advisor	X	X	1	1	1

6.6.2.3 Betweenness centrality of design team

The betweenness centrality of the design team is calculated using Gephi. The betweenness centrality is a measure that indicates the number of times a node acts as a bridge to connect other nodes in the network through their shortest path. The table below indicates the results of the betweenness centrality of the design team members in each stage of the design process. The additional roles, client and client advisor, and the project lead betweenness centrality increases in the concept design process and decreases as the process moves forward to the developed design and the technical design stage. The next section of this chapter will assess the controllability of knowledge diffusion of those design team members with higher results of betweenness centrality in each design stage.

Table 6.20 Betweenness centrality of all the design team members in each stage of the building design process

	Betweenness				
Design team	**Strategic brief**	**Preparation and brief**	**Concept design**	**Developed design**	**Technical design**
All additional roles	**0**	132	173.73	**155.89**	108.42
Client and client advisor	0	0	95.17	59.27	13.35
Project lead	28.5	303	329.37	327.51	286.72
Lead designer	2.5	0	56	237.88	204.16
Architect	4	0	90	165.83	276.47
Civil and structural engineer	0	24	96.33	311.90	103.85
Building services engineer	0	24	81.4	187.23	103.06
Cost consultant	0	0	0	37.46	8.97
Construction lead	**X**	**X**	0	0	0
Health and safety advisor	**X**	**X**	0	0	0

6.6.3 Centrality measures of the design process components

This section of the research will present the centrality measures of the building design process components. The results were calculated using Gephi. The centrality measures applied are the degree centrality, the closeness centrality, and the betweenness centrality.

6.6.3.1 Degree centrality of the design process components

Table 6.21 displays the degree centrality results of the design process components of each design process stage. The results indicate that the higher degree centrality design process component of the strategic definitions design stage is the strategic brief with a degree centrality of 14. The results indicate that the design process component with the highest degree centrality in the preparation and brief stage is the initial project brief with a degree centrality of 18. Moreover, the results for the concept design stage design process components indicate that the higher degree centrality is the concept design process components, which are the drawings of the concept design drawings with a degree centrality of 17. In addition, the design process component with the highest result in the developed design stage is a developed design process component, which consists of the drawings for the developed design of the building. The technical design stage results for the design process components indicate that the highest result of degree centrality is for technical design drawings with a degree centrality of 21. The degree centrality of design process components indicates the amount of information that is flowing to this process component; as the number increases it indicates an increase in the amount of information and knowledge that is flowing to this design process component.

Table 6.21 Degree centrality of all the design process components in each stage of the building design process

Codes	The design process component	Strategic definitions stage	Preparation and brief stage	Concept design stage	Developed design stage	Technical design stage
BC	**Business case**	4	-	-	-	-
AM	**Assembling and monitoring the project team**	**2**	**5**	**6**	**6**	**4**

PP	**Project program**	**4**	2	**9**	**10**	**10**
PF	**Previous projects feedback**	**4**	**-**	**-**	**-**	**-**
SB	**Strategic brief**	**14**	**-**	**-**	**-**	**-**
PO	**Project objectives**	**-**	**4**	**-**	**-**	**-**
QO	**Quality objectives**	**-**	**4**	**2**	**-**	**-**
SS	**Sustainability strategies**	**-**	**6**	**8**	**8**	**6**
PB	**Project budget**	**-**	**7**	**-**	**-**	**-**
FS	**Feasibility studies**	**-**	**4**	**-**	**-**	**-**
SI	**Site information**	**-**	**6**	**-**	**-**	**-**
PR	**Projects roles table**	**-**	**2**	**-**	**-**	**-**
CT	**Contractual tree**	**-**	**2**	**2**	**-**	**-**
HS	**Handover strategy**	**-**	**3**	**2**	**2**	**2**
RS	**Risk assessment**	**-**	**4**	**4**	**4**	**4**
SSE	**Schedule of services**	**-**	**2**	**-**	**-**	**-**
DR	**Design responsibility matrix**	**-**	**2**	**7**	**8**	**8**
IE	**Information exchange**	**-**	**2**	**4**	**4**	**4**
PE	**Project Execution plan**	**-**	**4**	**8**	**-**	**-**
IPB	**Initial Project Brief**	**-**	**18**	**-**	**-**	**-**
RD	**Research and Development aspects**	**-**	**-**	**6**	**6**	**-**
CS	**Construction Strategy**	**-**	**-**	**-**	**2**	**-**
HSS	**Health and Safety Strategy**	**-**	**-**	**4**	**4**	**-**
PA	**Planning Application**	**-**	**-**	**2**	**2**	**-**
OS	**Operational Strategy**	**-**	**-**	**2**	**2**	**2**
SP	**Stage Design Program**	**-**	**-**	**12**	**12**	**11**
FPB	**Final project brief**	**-**	**-**	**6**	**-**	**-**
PS	**Project strategies**	**-**	**-**	**10**	**6**	**10**
CI	**Cost information**	**-**	**-**	**12**	**13**	**4**
CD	**Concept design**	**-**	**-**	**17**	**-**	**-**
CP	**Change control process**	**-**	**-**	**-**	**2**	**2**
DD	**Developed design**	**-**	**-**	**-**	**19**	**-**
BCO	**Building Contract**	**-**	**-**	**-**	**-**	**2**
BRS	**Building Regulations Submission**	**-**	**-**	**-**	**-**	**2**
TD	**Technical Design**	**-**	**-**	**-**	**-**	**21**

6.6.3.2 Closeness centrality of the design process components

Table 6.22 displays the results of closeness centrality of the design process components of each design process stage. The results indicate that the lower closeness centrality design process components of the strategic definitions design stage are the strategic brief and the business case with a closeness centrality of 1. The results indicate that the design process components with the lowest closeness centrality in the preparation and brief stage are the project programme and the feasibility studies with a closeness centrality of 1. Moreover, the results for concept design stage design process components indicate that those with the lowest closeness centrality are the stage design programme with a closeness centrality of 1 and the drawings of the concept design with a degree centrality of 2. In addition, the lowest results for the developed design stage design process components are the stage design programme with closeness centrality of 2.33 and the sustainability strategies with closeness centrality of 2.5. The technical design stage results for the design process components indicate that the technical design drawings and the project programme are lowest with a closeness centrality of 2.29. The closeness centrality of the design process components indicates the average distance of the node to all nodes in the network of the design process stage; as the number decreases it indicates that the design process components are in a central location for the flow of information in the stage network, which indicates that it is significant in terms of knowledge diffusion in the design process stage.

Table 6.22 Closeness centrality of all the design process components in each stage of the building design process

Codes	The design process component	Strategic definitions stage	Preparation and brief stage	Concept design stage	Developed design stage	Technical design stage
BC	Business case	1	-	-	-	-
AM	Assembling and monitoring the project team	0	2.23	3.47	2.83	3.12
PP	Project program	2	1	3.2	3.08	2.29
PF	Previous projects feedback	0	-	-	-	-
SB	Strategic brief	1	-	-	-	-
PO	Project objectives	-	0	-	-	-
QO	Quality objectives	-	0	0	-	-
SS	Sustainability strategies	-	2.42	0	2.5	2.5
PB	Project budget	-	2.08	-	-	-
FS	Feasibility studies	-	1	-	-	-
SI	Site information	-	3.93	-	-	-
PR	Projects roles table	-	2.38	-	-	-
CT	Contractual tree	-	2.38	0	-	-
HS	Handover strategy	-	0	0	0	0
RS	Risk assessment	-	0	0	0	0
SSE	Schedule of services	-	0	-	-	-
DR	Design responsibility matrix	-	2.38	0	3.5	2.65
IE	Information exchange	-	0	0	0	3.59
PE	Project Execution plan	-	2.25	0	-	-
IPB	Initial Project Brief	-	2.75	-	-	-
RD	Research and Development aspects	-	-	2.8	3.75	-
CS	Construction Strategy	-	-	-	2.88	-
HSS	Health and Safety Strategy	-	-	0	0	-
PA	Planning Application	-	-	0	0	-
OS	Operational Strategy	-	-	0	0	3.94
SP	Stage Design Program	-	-	1	2.33	2.76
FPB	Final project brief	-	-	3.6	-	-
PS	Project strategies	-	-	2.7	3.08	2.76

CI	**Cost information**	-	-	**3.25**	**2.58**	**0**
CD	**Concept design**	-	-	**2**	-	-
CP	**Change control process**	-	-	-	**0**	**3.17**
DD	**Developed design**	-	-	-	**3.33**	-
BCO	**Building Contract**	-	-	-	-	**0**
BRS	**Building Regulations Submission**	-	-	-	-	**3.06**
TD	**Technical Design**	-	-	-	-	**2.29**

6.6.3.3 Betweenness centrality of the design process components

Table 6.23 displays the results of betweenness centrality of the design process components of each design process stage. The results indicate that the highest betweenness centrality for the design process components of the strategic definitions design stage is the strategic brief with a betweenness centrality of 18. The results indicate that the design process components with the highest betweenness centrality in the preparation and brief stage are the initial project brief with betweenness centrality of 228.5, and the project execution plan with betweenness centrality of 120. Moreover, the results for the concept design stage design process components indicate that the highest betweenness centrality results are for final project brief with betweenness centrality of 256.63 and concept design process components which is the drawing of the concept design drawings and the Final project brief with 91.6. In addition, the design process components with the highest results for the developed design stage are cost information with betweenness centrality of 277.76 and stage design programme with betweenness centrality of 318.74. The technical design stage results for the design process components indicate that the highest results of betweenness centrality are for stage design programme with betweenness centrality of 238.16 and technical design component, which is the drawings of the technical design of the building, with betweenness centrality of 347.83.

Table 6.23 Betweenness centrality of all the design process components in each stage of the building design process

Codes	The design process component	Strategic definitions stage	Preparation and brief stage	Concept design stage	Developed design stage	Technical design stage
BC	Business case	7	-	-	-	-
AM	Assembling and monitoring the project team	0	25	9.5	38	46.48
PP	Project program	7	0	62.5	181.66	68.87
PF	Previous projects feedback	0	-	-	-	-
SB	Strategic brief	18	-	-	-	-
PO	Project objectives	-	0	-	-	-
QO	Quality objectives	-	0	0	-	-
SS	Sustainability strategies	-	4	0	29.06	4.79
PB	Project budget	-	19	-	-	-
FS	Feasibility studies	-	10.5	-	-	-
SI	Site information	-	18	-	-	-
PR	Projects roles table	-	0	-	-	-
CT	Contractual tree	-	0	0	-	-
HS	Handover strategy	-	0	0	0	0
RS	Risk assessment	-	0	0	0	0
SSE	Schedule of services	-	0	-	-	-
DR	Design responsibility matrix	-	0	0	21.66	38.5
IE	Information exchange	-	0	0	0	44
PE	Project Execution plan	-	120	0	-	-
IPB	Initial Project Brief	-	228.5	-	-	-
RD	Research and Development aspects	-	-	23.4	9.06	-
CS	Construction Strategy	-	-	-	0	0
HSS	Health and Safety Strategy	-	-	0	0	-

PA	**Planning Application**	**-**	**-**	**0**	**0**	**-**
OS	**Operational Strategy**	**-**	**-**	**0**	**0**	**0**
SP	**Stage Design Program**	**-**	**-**	**34**	**318.74**	**238.16**
FPB	**Final project brief**	**-**	**-**	**91.6**	**-**	**-**
PS	**Project strategies**	**-**	**-**	**70.9**	**70.25**	**111.59**
CI	**Cost information**	**-**	**-**	**77.4**	**277.76**	**0**
CD	**Concept design**	**-**	**-**	**256.63**	**-**	**-**
CP	**Change control process**	**-**	**-**	**-**	**0**	**0**
DD	**Developed design**	**-**	**-**	**-**	**216.81**	**-**
BCO	**Building Contract**	**-**	**-**	**-**	**-**	**0**
BRS	**Building Regulations Submission**	**-**	**-**	**-**	**-**	**0**
TD	**Technical Design**	**-**	**-**	**-**	**-**	**347.83**

6.7 Assessment of the controllability of knowledge diffusion in the building design process stages

This section of the research will assess the controllability of the significant aspect of the building design process of each stage of the building design process in terms of knowledge diffusion. The method to be used to determine the significant design tasks, design team, and design process components that are going to be applied is using their centrality measures, which determine their centrality in the flow of information in the building design process stage. These measures can significantly assess the importance of the three aspects of the building design process in terms of knowledge diffusion in the design process stage. The following section indicates the use of the centrality measures to indicate the controllability of knowledge diffusion in the building design process stage.

6.7.1 Assessment of design task controllability of knowledge diffusion in the building design process stage

The assessment of design task controllability of knowledge diffusion in the building design process stage depends on the result of the design task closeness centrality in the stage network. As the closeness centrality of a design task decreases it indicates the significance of this design task in the diffusion of knowledge in the building design process stage. Table.6.24 consists of the significant design tasks that have the lowest centrality in each design process stage.

Table.6.24 Closeness centrality of the significant knowledge diffusion design tasks in the design process stage

The design task	Closeness centrality	The design stage
S0T1	1	The strategic definition stage
S0T8	1	The strategic definition stage
S0T15	1	The strategic definition stage
S1T13	1	The preparation and brief stage
S1T17	1	The preparation and brief stage
S2T34	1	Concept design stage
S2T36	1	Concept design stage
S3T22	1	Developed design stage
S3T35	2.52	Developed design stage
S4T22	1	Technical design stage
S4T36	2.05	Technical design stage

Fig. 6.17 indicates the information flow of each of the three significant design tasks of the strategic definition stage. The information that flows from these three significant design tasks is as follows. First, S0T1 is a design task that required to be established by

the client and client advisor; it provides the business case to contribute to the strategic brief of the project. The S0T1 section in Fig. 6.17 indicates that the information is flowing from design task S0T1 to the business case from the client and client advisor as well as showing that the business case is connected to the project lead, which will deliver the knowledge to the strategic brief design process component. Second, S0T8 is a design task that is required to be established by the lead designer to provide feedback from other similar projects to the current one. Section S0T8 of Fig. 6.17 indicates that the information is flowing from design task S0T8 to the previous project feedback component as well as showing that the previous project feedback is connected to the project lead, which delivers the knowledge to the strategic brief component. Third, S0T15 is a design task that is required to be established by all the project roles, which is the contribution of the preparation of the stage's strategic brief. The flow of information from this design task is shown in Fig. 6.17, which indicates that the design task is connected to all the project roles, which passes the information about this design task to the strategic brief of the stage.

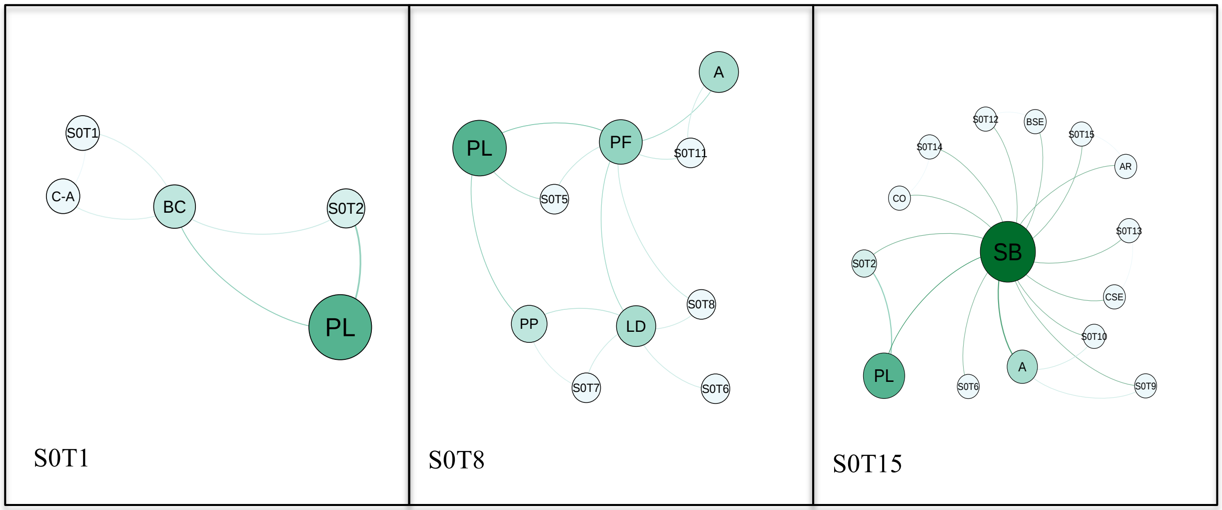


Fig. 6.17 Flow of information of each of the three significant design tasks of the strategic definitions stage

Fig. 6.18 indicates the flow of information of each of the two significant design tasks of the preparation and brief stage. The information that flows from these two significant design tasks is as follows. First, S1T13 is a design task that required to be established by the lead designer to comment on the provided project programme. The flow of information from this design task is shown in Fig. 6.18, which indicates that the design task is connected to the design lead and the project programme, from which information will flow to the initial project brief. Second, S1T17 is a design task that required to be established by the architect and it is connected to the feasibility studies of the project, from which information will flow to the project lead, which is contributing to the feasibility study and the initial project brief.

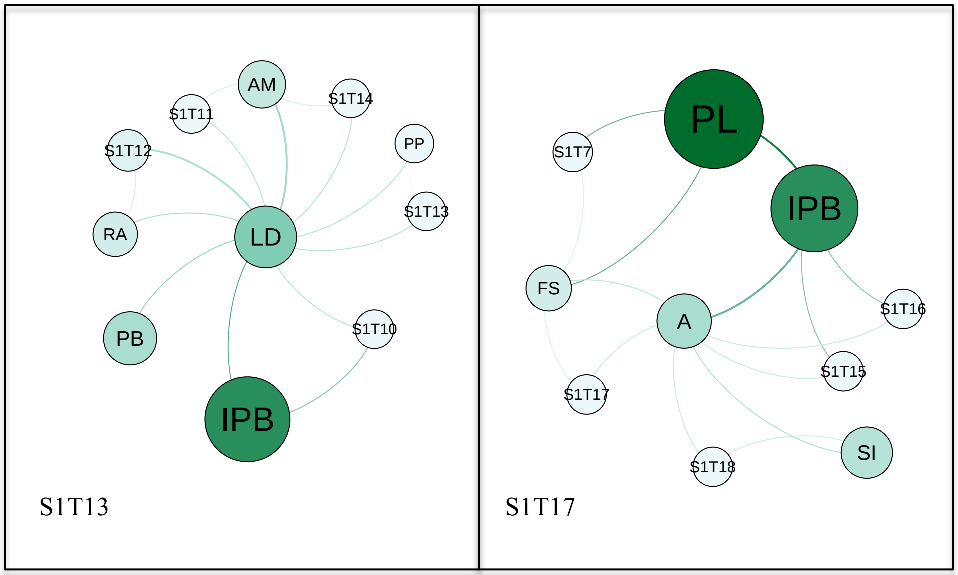


Fig. 6.18 Flow of information of each of the two significant design tasks of the preparation and brief stage

Fig. 6.19 indicates the information flow of each of the two significant design tasks of the concept design stage. These flows of information are as follows. First, S2T34, which is a design task that is required to be established by the cost consultant as the primary cost of the project, with the assistance of the lead designer. Fig. 6.19 indicates the flow of information on cost from the connectivity of the design task to the cost consultant and the design lead, from where it flows to the concept design drawings. Second, S2T36 is a design task that is required to be established by the health and safety engineer to develop strategies for health and safety in the building design. The flow of information is indicated in Fig. 6.19, which is from the design task that is connected to the health and safety engineer and the health and safety strategies component that passes information to the concept design through all the roles that are connected to the health and safety strategies component.

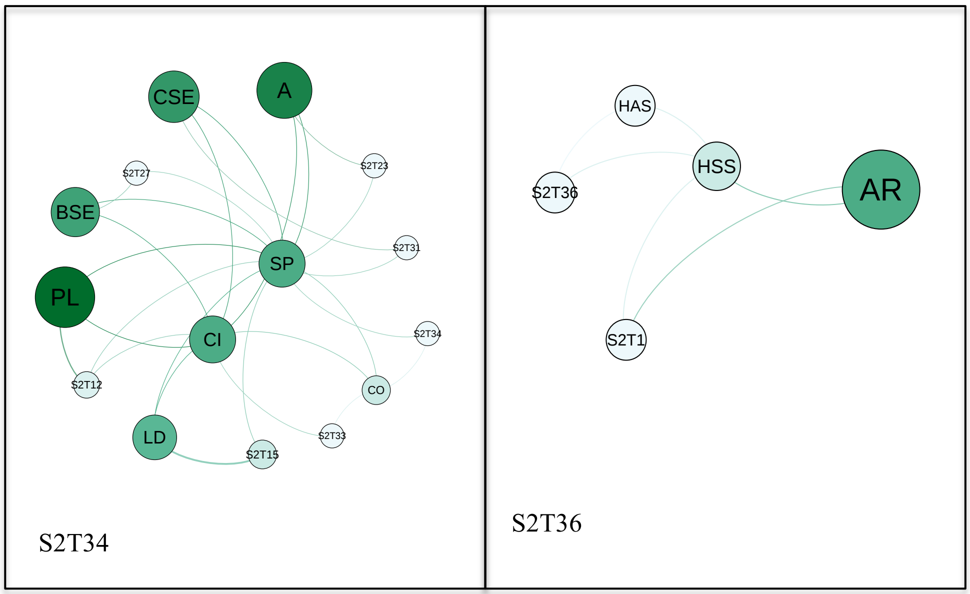


Fig. 6.19 Flow of information of each of the two significant design tasks of the concept design stage

Fig. 6.20 indicates the information flow of each of the two significant design tasks of the developed design stage. These flows of information are as follows. First, S3T22, which is a design task that is required to be established by the architect to assist the lead designer to establish the stage's design programme component. The flow of information from this design task is shown in Fig. 6.20, which indicates that the knowledge is diffused from the design task to the architect and the design lead to establish the stage's design programme, which is connected to all design team members because each has to contribute to and follow this programme to establish the developed design drawings. Second, S3T35 is a design task that is required to be established by the health and safety engineer to develop the health and safety strategies in accordance with the comments of the design team. The flow of information is shown in Fig. 6.20, which indicates that the task is connected to all the roles, which will pass the health and safety information to all the design team and to the drawings component of the developed design.

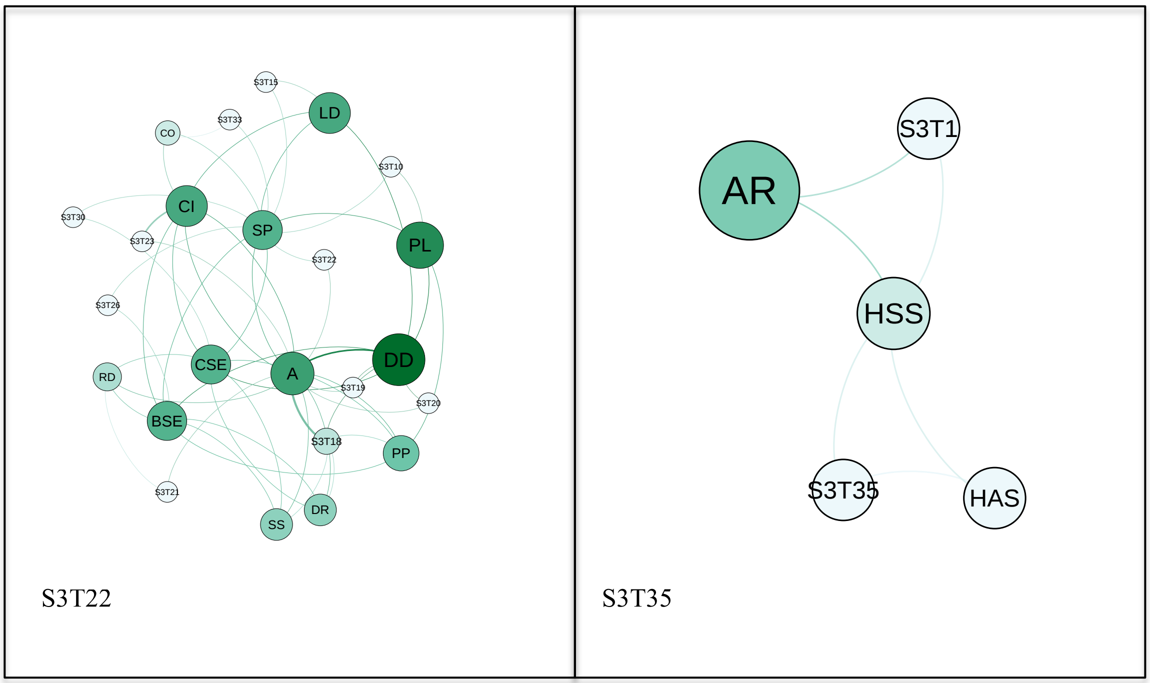
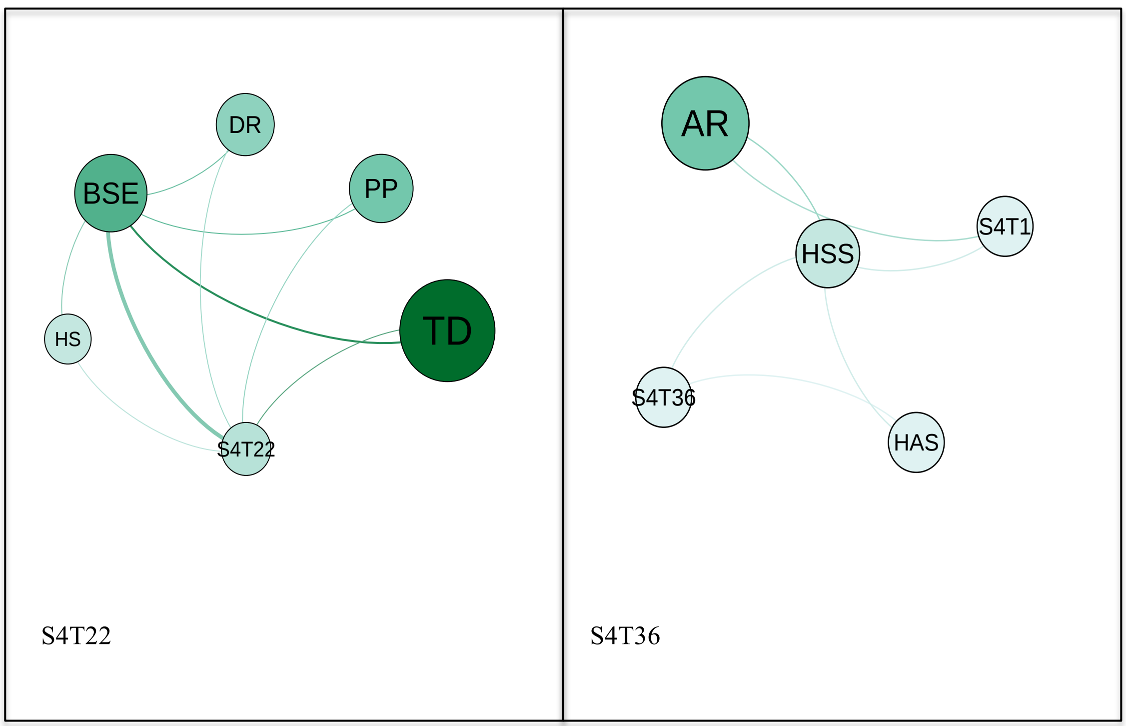


Fig. 6.20 Flow of information of each of the two significant design tasks of the developed design stage

Fig. 6.21 indicates the information flow of each of the two significant design tasks of the technical design stage. These flows of information are as follows. First, S4T22, which is a design task that is required to be established by the building services engineer to prepare the building services technical design in accordance with the design responsibility matrix and building programme. The flow of information of this design task is indicated in Fig. 6.21, where the knowledge diffusion flows from the design task to the building services engineer, to the design responsibility matrix, project programme and the building's technical design drawings. Second, S4T36 is a design task that required to be established by all project roles to contribute to the health and safety strategies of the building design in the technical design stage. The information flows as shown in Fig. 6.21: from the design task to the health and safety strategies component from all roles in the project design, which will diffuse this information to all the project design team.



The Fig. 6.21 Flow of information of each of the two significant design tasks of the technical design stage

6.7.2 Assessment of the design team members' controllability of knowledge diffusion in the building design process stages

The assessment of the design team members' controllability of knowledge diffusion in the building design process stages depends on the results of the team degree centrality, closeness centrality, and betweenness centrality. Each of the three-centrality measures indicates an important aspect of the knowledge diffusion. The degree centrality of a design team member indicates the amount of information that is diffused from the design team member, whilst the closeness centrality of a design team member indicates how central the design team is to easily diffuse knowledge in the design process stage. The betweenness centrality indicates the importance of the design team in passing information through the design process stage.

6.7.2.1 The degree centrality of the design team and knowledge diffusion

Table 6.20 displays the results for design team degree centrality, which measures the amount of knowledge diffusion from the design team members. The results indicate that each design team member's knowledge diffusion varies from stage to stage. Thus, this section of the research will indicate the design stages where the design team members are diffusing knowledge more than in other stages. The team comprises the all additional roles category, client and client advisor, project lead, lead designer, architect, civil and structural engineer, building services engineer, and cost consultant.

The results for degree centrality of the all-additional roles category, which is 12 degrees of centrality, indicate that the concept design stage is the highest stage in which all the roles are diffusing knowledge. In addition, Fig. 6.22 shows the knowledge flow that the all additional roles category is diffusing in the concept design stage, which design knowledge is contributing to establishing health and safety strategies, information exchange through design stages, final project brief, project programme, design responsibility matrix, and sustainability strategies and concept design drawings. Therefore, this design team member is the most significant one in terms of amount of information diffused towards the establishment of the previous components as well as the concept design drawings.

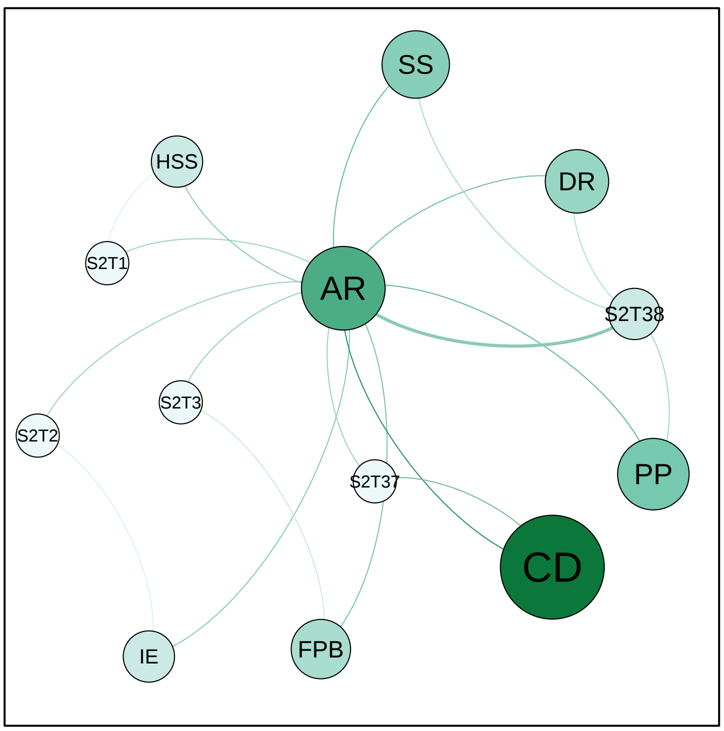


Fig. 22 Flow of knowledge that the all-additional roles category is diffusing in the concept design stage

The client and client advisor category had a result of 6 degrees of centrality in the preparation and brief, concept design, and developed design stages, which are the highest stages in which they diffused knowledge. In addition, Fig. 6.23 indicates that the flow of knowledge the client and client advisor is diffusing in each of the three design stages the resulted a higher degree centrality in. Fig. 6.23 indicates that in each design stage the client and the client advisor are diffusing knowledge differently. In the preparation and brief stage, they contribute to establishing the project budget, the project objectives, and the quality objectives of the building design, which all diffuse knowledge to the initial project brief. In the concept design stage, they contribute to the project strategies and final project brief, which will diffuse knowledge for establishment of the concept design. In the developed design they contribute to establishing the cost information, which will diffuse knowledge to the developed design.

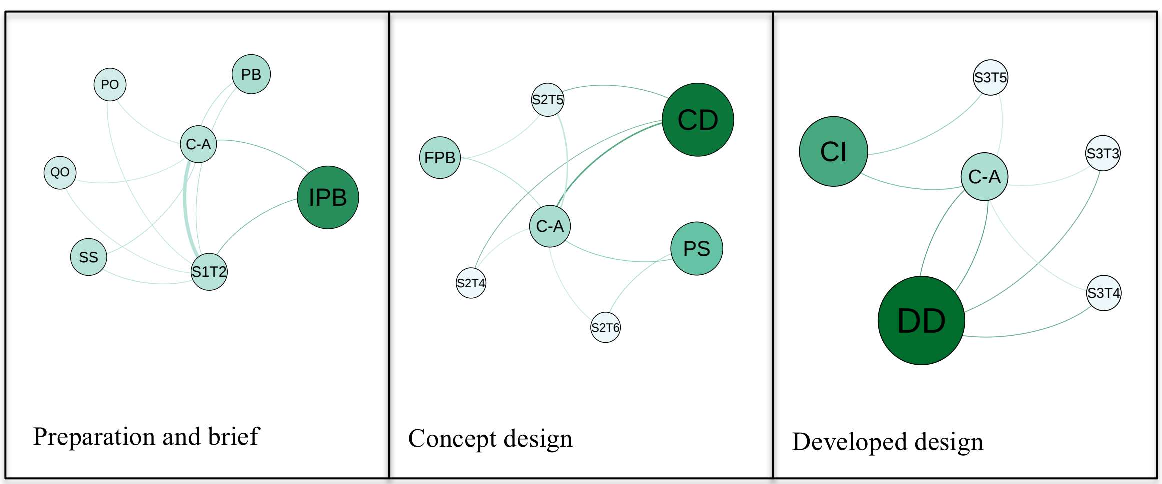


Fig. 6.23 Flow of knowledge that the client and client advisor are diffusing in each of the three design stages

The results of degree centrality of the project lead which is 22 degree centrality indicates that the preparation and brief stage is the highest stage that the project lead is diffusing knowledge in. In addition, Fig. 6.24 indicates that the flow of knowledge that the project lead is diffusing in the preparation and brief stage is contributing to establishing the project roles table, contractual tree, design responsibility matrix, information exchange through the stages, handover strategies, risk assessment, assembling and monitoring the design team, sustainability strategies, quality objectives, feasibility studies, project objectives, project budget, and project execution plan. The project lead design team member is the most significant design team member in terms of amount of information diffusion towards the establishment of the previous process components as well as the initial project brief.

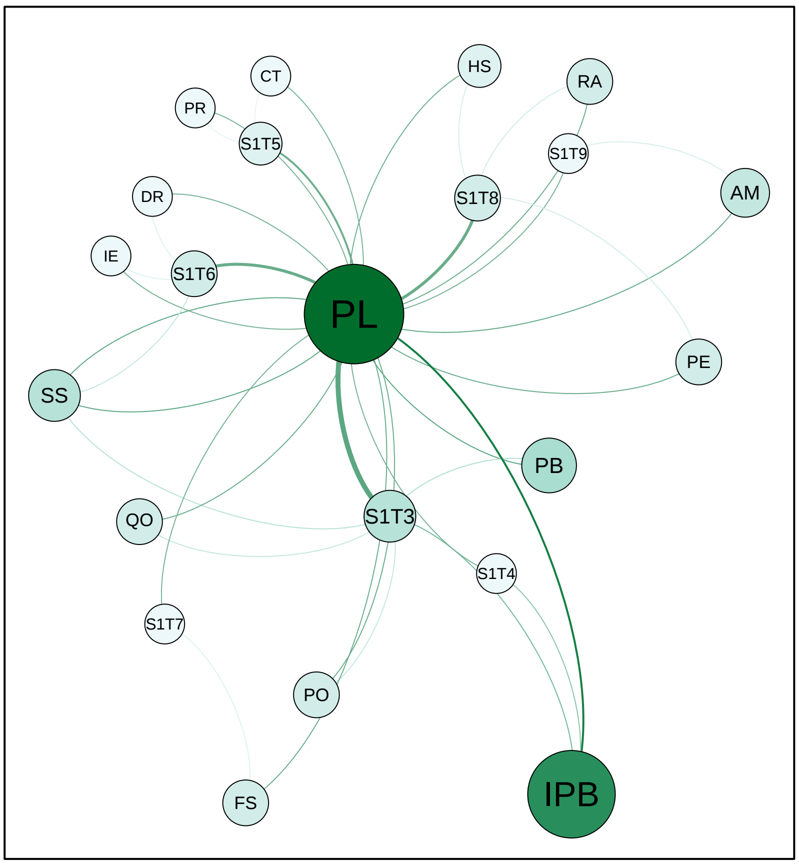


Fig. 6.24 Flow of the knowledge that the project lead is diffusing in the preparation and brief stage

The result of degree centrality of the lead designer, which is 15-degree centrality, indicates that the technical design stage is the highest stage that the lead design is diffusing knowledge in. In addition, Fig. 6.25 indicates that the flow of knowledge that the project lead is diffusing in the technical design stage is contributing to establishing the stage design programme, maintenance strategies, quality objectives, operational strategies, assembling, and monitoring the design team. The lead designer tem member is the most significant design team member in terms of diffusing large amounts of knowledge in the technical design stage towards the establishment of the previous process components and of the technical design drawings.

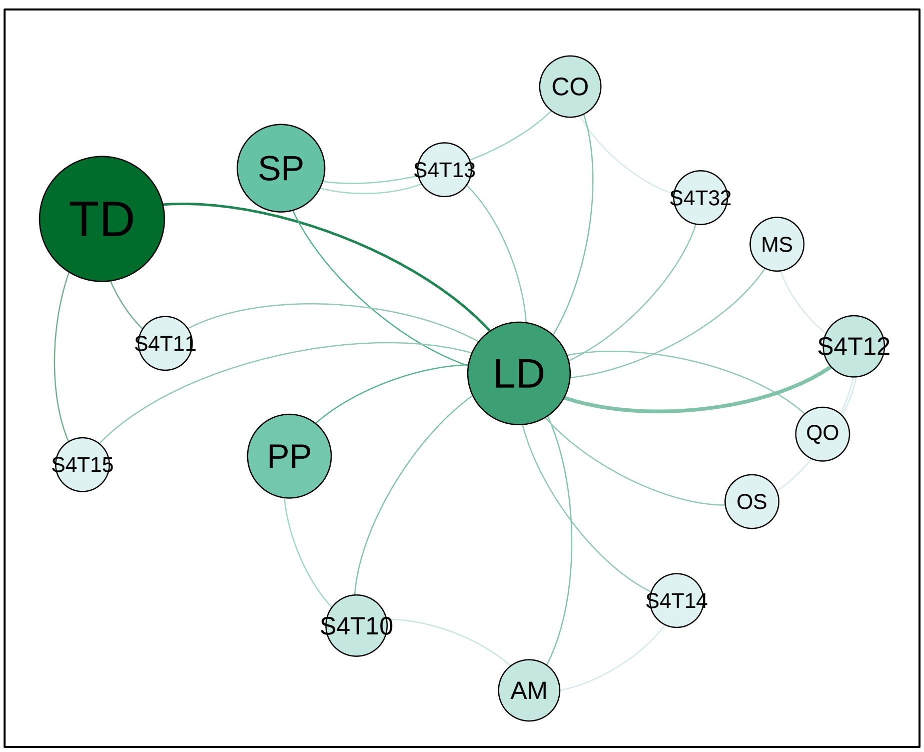


Fig. 6.25 Flow of the knowledge that the lead designer is diffusing in the technical design stage

The result of degree centrality of the architect, which is 16-degree centrality, indicates that the concept design stage is the highest stage that the architect is diffusing knowledge in. In addition, Fig. 6.26 indicates that the flow of the knowledge that the architect is diffusing in the concept design stage is contributing to establishing the health and safety strategies, project programme, information exchange through the process, design responsibility matrix, sustainability strategies, and the final project brief. The architect team member is the most significant design team member in terms of knowledge diffusion of design towards the establishment of the previous process components as well as the establishment of the concept design drawings.

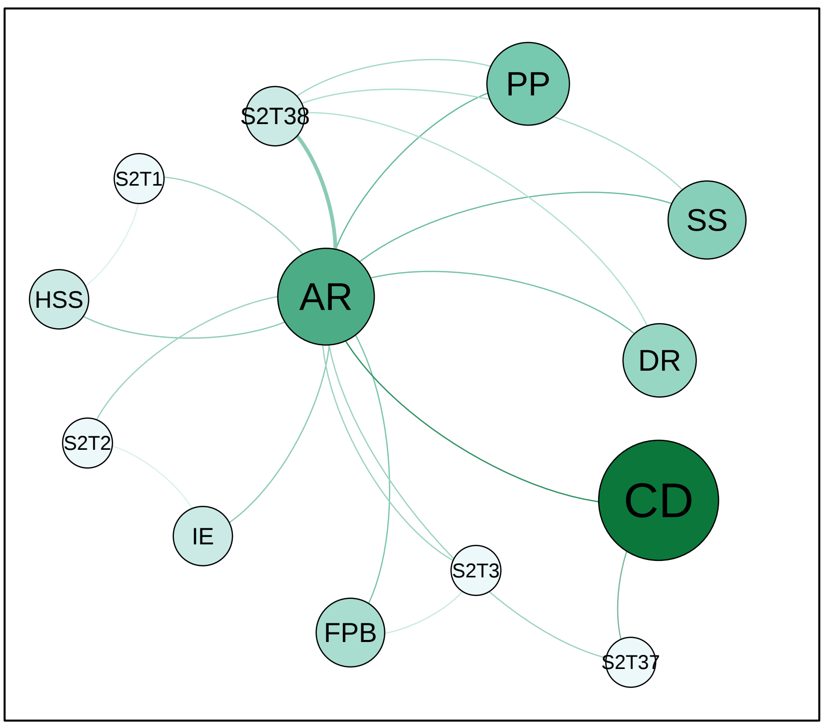


Fig. 6.26 Flow of the knowledge that the architect is diffusing in the concept design stage

The result of degree centrality of the civil and structural engineer, which is 13-degree centrality, indicates that the concept design stage is the highest stage that the civil and structural engineer is diffusing knowledge in. In addition, Fig. 6.27 indicates that the flow of knowledge that the civil and structural engineer is diffusing in the concept design stage is contributing to establishing the design responsibility matrix, sustainability strategies, the project programme, research and development, project execution plan, project strategies, cost information, and stage design program. The civil and structural engineer is the most significant design team member in terms of knowledge diffusion to the previous process components as well as the establishment of the concept design.

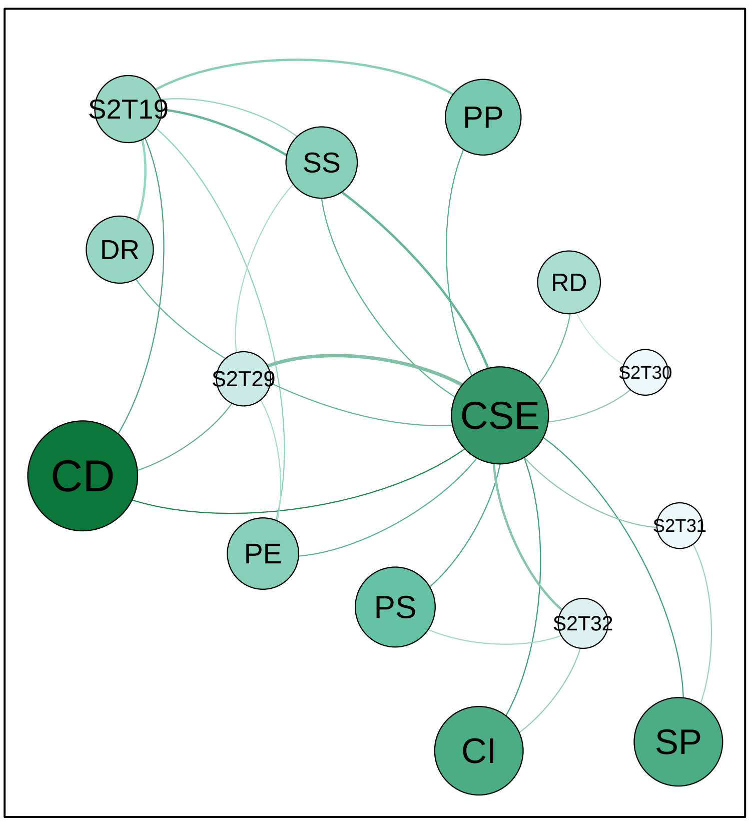


Fig. 6.27 Flow of the knowledge that the civil and structural engineer is diffusing in the concept design stage

The result of degree centrality of the Building services engineer, which is 14-degree centrality, indicates that the concept design stage is the highest stage that the Building services engineer is diffusing knowledge in. In addition, Fig. 6.28 indicates that the flow of knowledge that the building services engineer is diffusing in the concept design stage is contributing to establishing the project programme, sustainability strategies, design responsibility matrix, research development, project execution plan, project strategies, cost information, and the stage design programme. The building services engineer is the most significant design team member in terms of knowledge diffusion to the previous components in the concept design stage as well as the concept design drawings in the concept design stage.

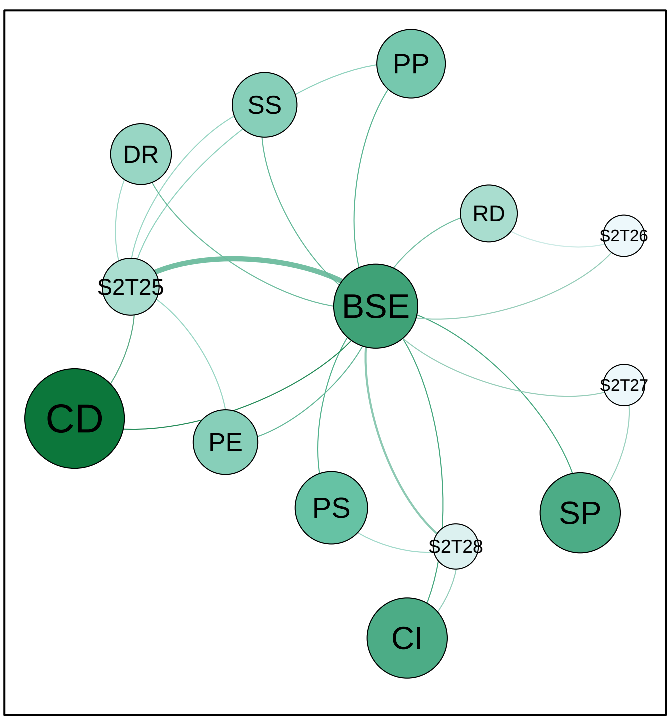


Fig. 6.28 Flow of the knowledge that the building services engineer is diffusing in the concept design stage

In the strategic diffusion stage, the degree centrality result for the cost consultant is 2; however, the amount of knowledge increases to 4-degree centrality in the rest of the design process stages. Fig. 6.29 indicates the cost consultant's knowledge flow in the concept design stage, which is knowledge that is contributing to establishing the design stage programme, and the project's cost information.

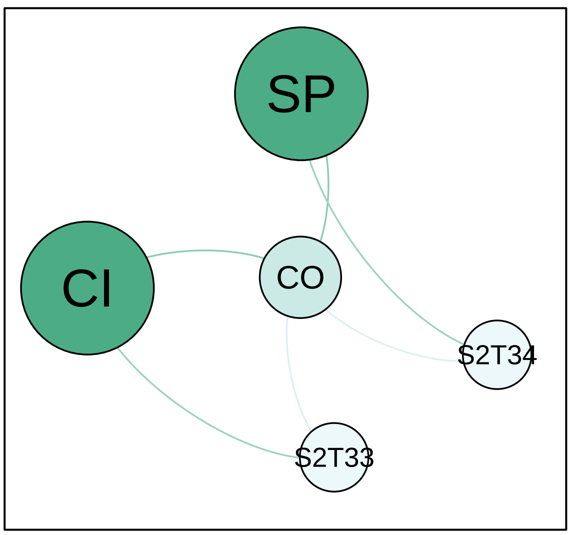


Fig. 6.29 Flow of the knowledge that the cost consultant is diffusing in the concept design stage

6.7.2.2 The closeness centrality of the design team and knowledge diffusion

Table 6.21 indicates the results of closeness centrality of design team members, which measures how central the location of the design team is in diffusing knowledge of design in the design process stage. The results indicate that the results of closeness centrality for each design team member are different in each design stage, which indicates a change of location in terms of knowledge diffusion of design in each stage. This section of the research will indicate the most central design team member in terms of knowledge diffusion in the design process stages.

The closeness centrality results for the design team members in the strategic definition stage indicate that the lead designer is the most central design team member in this design stage. Fig. 6.30 shows the process of knowledge diffusion from the lead designer in the strategic definition stage. The process indicates that the information flows to the project programme and the previous projects' feedback. This knowledge flows to two design team members who are contributing to the stage: the project lead and the architect, who deliver the information for the establishment of the strategic brief.

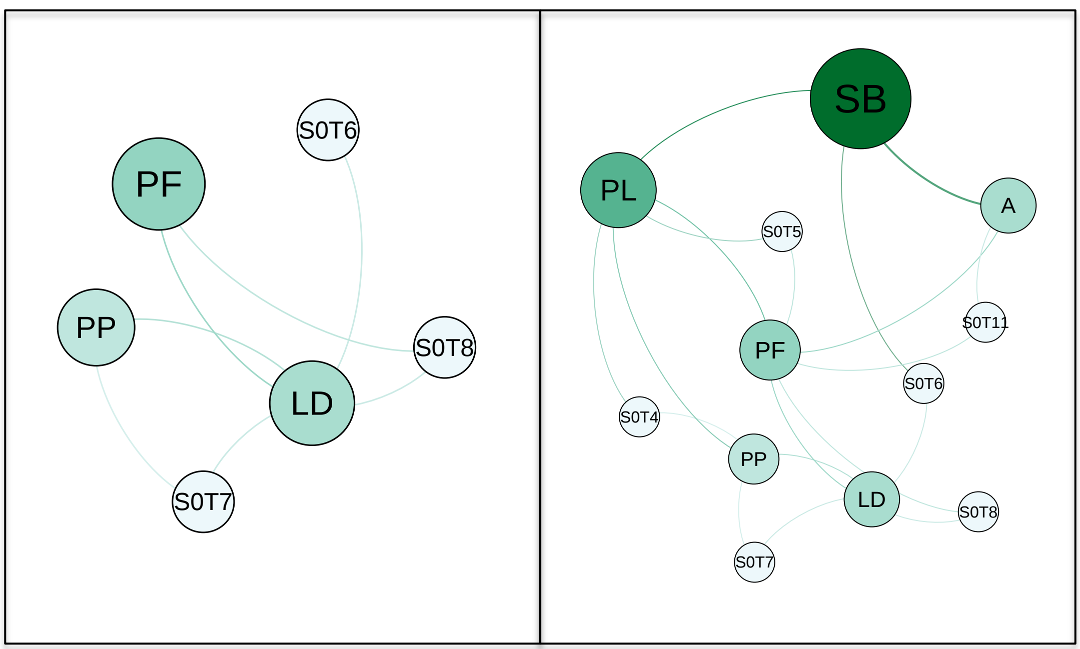


Fig. 6.30 Process of the knowledge diffusion from the lead designer in the strategic definition stage

The closeness centrality results for the design team members in the preparation and brief stage indicate that the project lead is the most central design team member in this design stage. Fig. 6.31 shows process of knowledge diffusion from the project lead in the preparation and brief stage. The process indicates that the information flows to several design process components that are connected to all the design team members in the design process stage and these information flows establish the initial project brief.

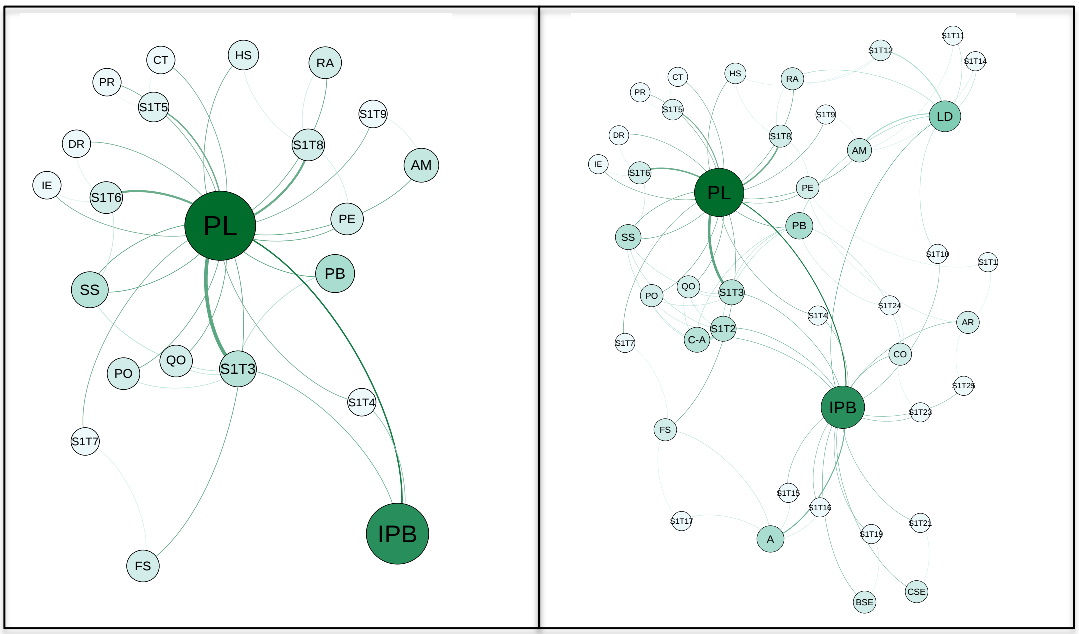


Fig. 6.31 Process of the knowledge diffusion from the project lead in the preparation and brief stage

The closeness centrality results for the design team members in the concept design stage indicate that the all additional roles category is the most central design team member in this design stage. Fig. 6.32 indicates process of knowledge diffusion from this category in the concept design stage. The process indicates that the information flows to several design process components that are connected to all the design team members in the design process stage and these information flows establish the concept design drawings.

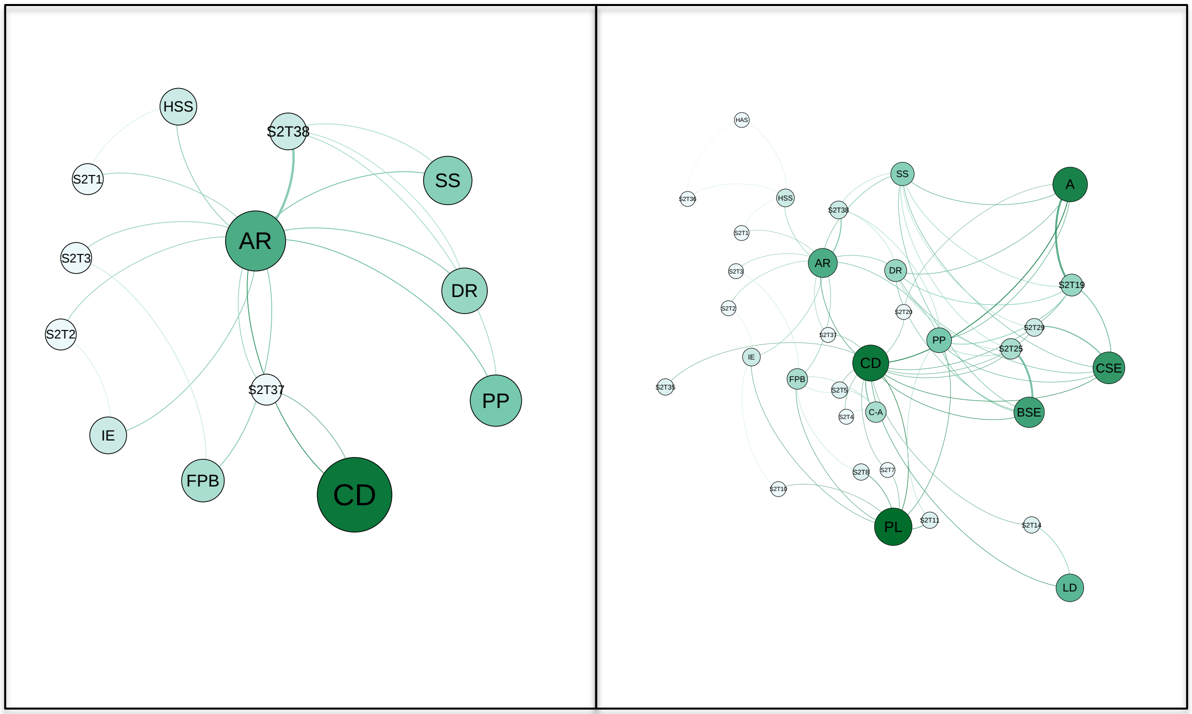


Fig. 6.32 Process of the knowledge diffusion from all additional roles in the concept design stage

The closeness centrality results for the design team members in the developed design stage and technical design stage indicate that the architect is the most central design team member in these two design stages. Fig. 6.33 shows the process of the knowledge diffusion from the architect in both the developed design stage and the technical design stage. The process indicates that the information flows to several design process components that are connected to all the design team members in the design process stages and these information flows establish the drawings of the developed and the technical design of the project.

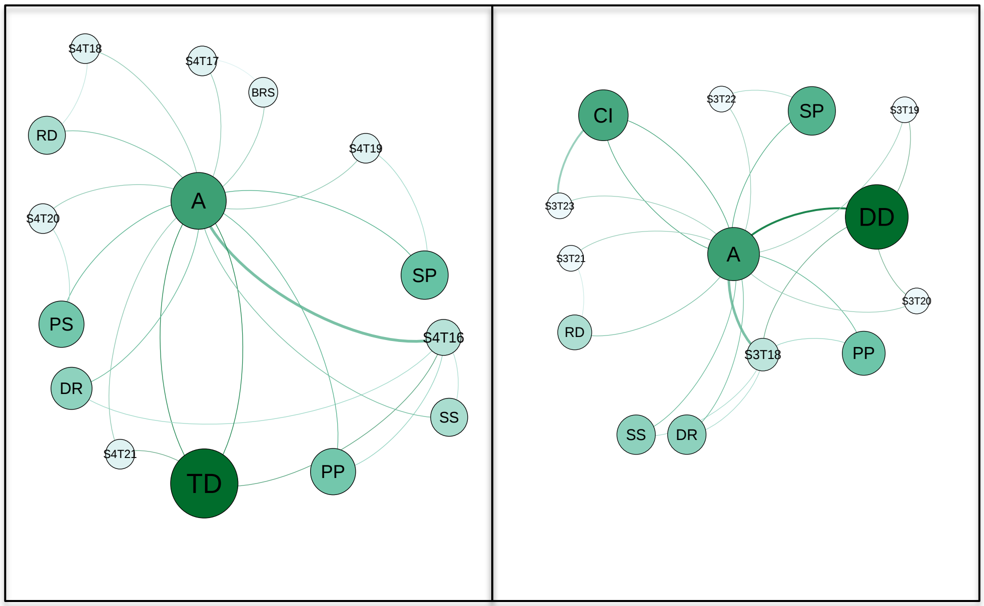


Fig. 6.33 Process of the knowledge diffusion from the architect in both the developed design stage and the technical design stage

6.7.2.3 The betweenness centrality of the design team and knowledge diffusion

Table 6.22 displays the betweenness centrality results for the design team members, which measures the importance of the design team in passing information through the design process stage. The results indicate that the project lead has the highest betweenness centrality in each of the design process stages. This indicates that the most important design team member in terms of passing information through the design process stages is the project lead. Disconnection of the project lead from the design process stage will significantly affect the knowledge diffusion of the whole process stage. This section of the research will indicate the effect of disconnection of the project lead on knowledge diffusion in each design stage.

Fig. 6.34 shows the betweenness centrality results for the project lead in each design process stage. The most significant result is in the concept design stage. Thus, this section will discuss the effect of disconnection on the project lead's diffusion of knowledge in the concept design stage.

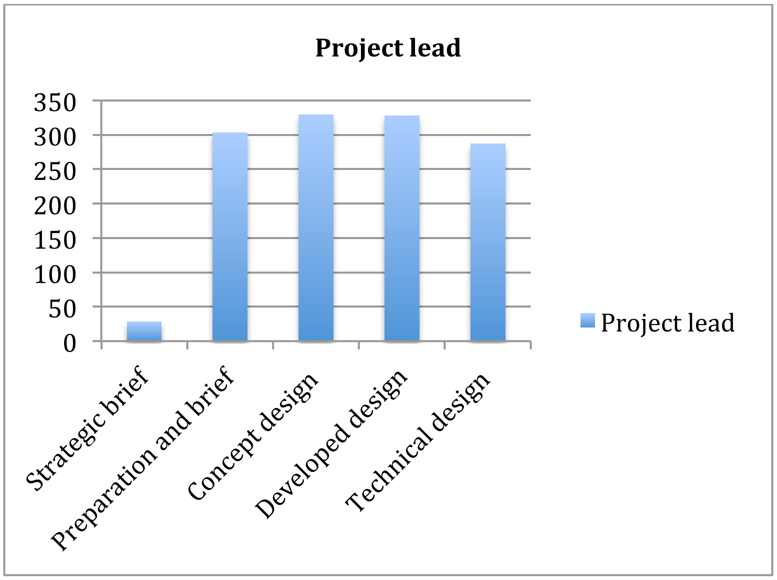


Fig. 6.34 Betweenness centrality of the project lead in each design process stage

The disconnection of the project lead from the concept design stage network will significantly affect several design process components, which are indicated in Fig. 6.35; they are the final project brief, project execution plan, project programme, information flow of the design stages, cost information, stage design programme, assembling and monitoring the design team. Each of the previous components will significantly affect the outcomes of the concept design drawings. The following will indicate how the disconnection of the project lead will affect the flow of information to these design process components and how they affect the outcomes of the concept design drawings.

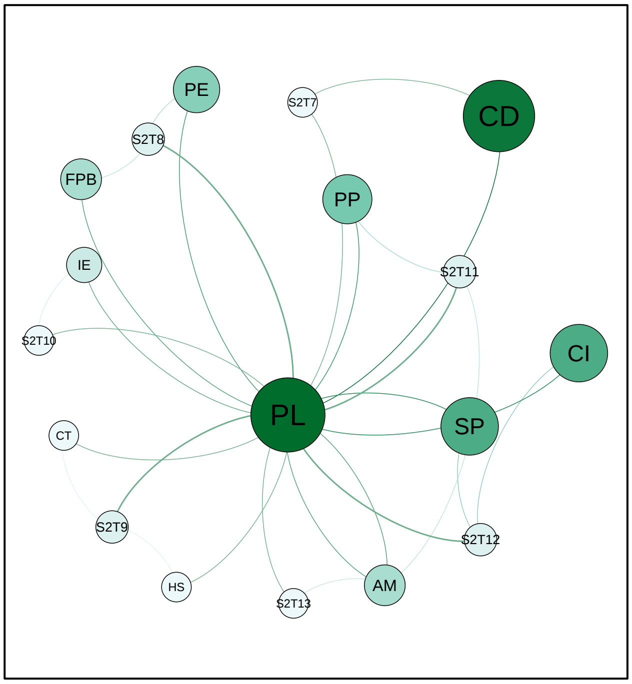


Fig. 6.35 Connectivity of the project lead to the process components in the concept design stage

Final project brief: Fig. 6.36 shows the information that flows to establish the final project brief in the concept design stage, which consists of three design tasks, S2T5, S2T3, and S2T8. The task that will be disconnected is S2T8, which is to collect and agree on the final changes and issue the final project brief, which is performed by the project lead. The disconnection of this design task will significantly affect the information flow to the concept design drawings because the information required for the final project brief will be lost.

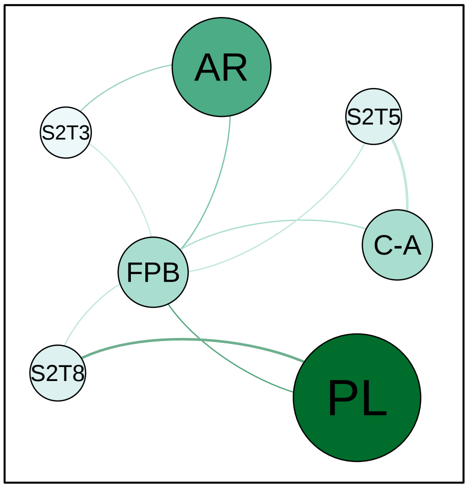


Fig. 6.36 Information flows to establish the final project brief in the concept design stage

6.7.3 Assessment of the design process components' controllability of knowledge diffusion in building design process stages

The assessment of the design process components controllability of knowledge diffusion in the building design process stages depends on the results of the components' degree centrality, closeness centrality, and betweenness centrality. Each of the three centrality measures indicates important aspects of the knowledge diffusion. The degree centrality of the design process components indicates the amount of information that is delivered to the design process component in order to establish it in the design process stage. The closeness centrality of the design process components is indicating how central the location of the design process components to easily receive the knowledge of the design in the design process stage. The betweenness centrality indicates the importance of the design process component in passing information through the design process stage.

6.7.3.1 The degree of centrality of the design process components and the knowledge diffusion

The degree centrality of a design process component indicates the amount of information that is delivered from the design task and design team member to the design process component in order to establish it. Table 6.23 displays the degree centrality results for the design process components in each design stage.

The results of the strategic definition stage indicate that the design process component with the highest degree centrality is the strategic brief component with 14-degree centrality. Fig. 6.37 shows the flow of knowledge that the strategic brief component is receiving in the strategic definition stage. This information is received by the project lead, additional roles, building services engineer, civil and structural engineer, and cost consultant. The strategic brief is the most significant design process component in terms of receiving information because it is connected to a lot of design team members who deliver information to it from other design process components and design tasks.

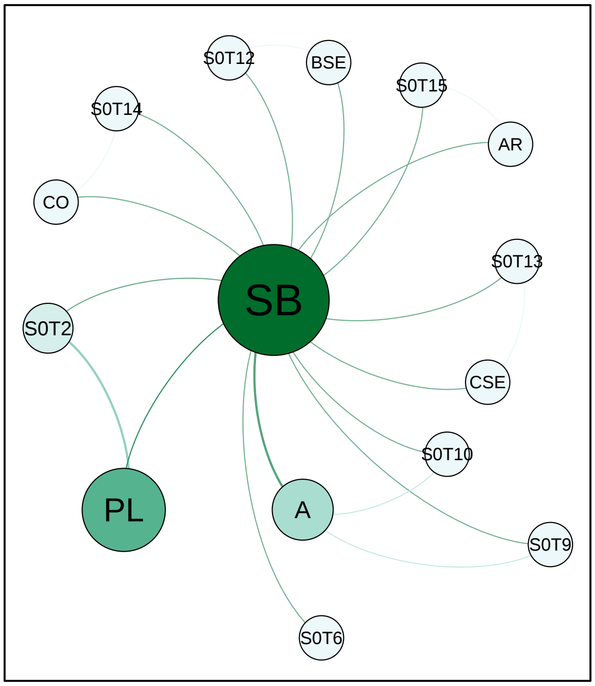
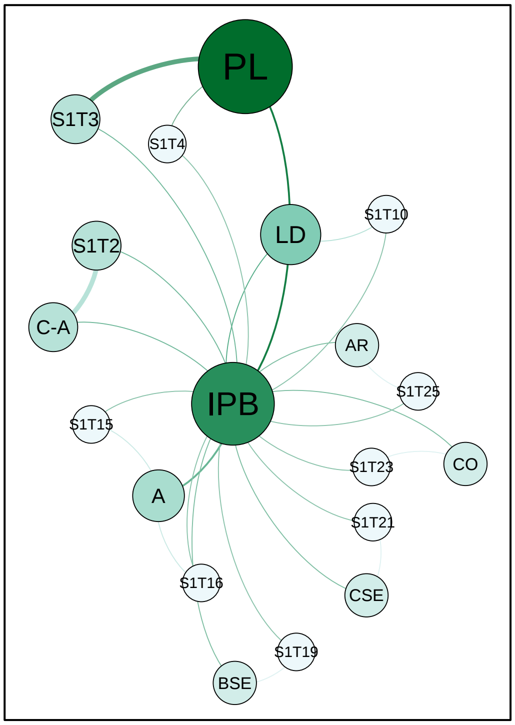


Fig. 6.37 Flow of knowledge that all strategic brief components are receiving in the strategic definition stage

The results of the preparation and brief stage indicate that the design process component with the highest degree of centrality is the initial project brief component with 18-degree centrality. Fig. 6.38 shows the flow of knowledge that this component is receiving in the preparation and brief stage. This information is received from all the design team members of the design. This indicates that the initial project brief is the most significant design process component in the preparation and brief stage in terms of receiving information because it is connected to a lot of design team members who are delivering information to it from other design process components and design tasks.



The Fig. 6.38 Flow of knowledge that the initial project brief component is receiving in the preparation and brief stage

The results of the concept design stage indicate that the design process component with the highest degree centrality is the concept design drawings component with 17-degree centrality. Fig. 6.39 shows the flow of knowledge that the concept design component is receiving in the concept design stage. This information is received from all the design team members of the design.

This indicates that the concept design drawings component is the most significant design process component in the concept design stage in terms of receiving information because connected to a lot of design team members who are delivering information to it from other design process components and design tasks.

The results of the developed design stage indicate that the design process component with the highest degree of centrality is the developed design drawings component with 19-degree centrality. Fig. 6.40 shows the flow of knowledge that the developed design component is receiving in the developed design stage. This information is received from all the design team members of the design. This indicates that the developed design drawings component is the most significant design process component in the developed design stage in terms of receiving information because it is connected to a lot of design team members who are delivering information to it from other design process components and design tasks.

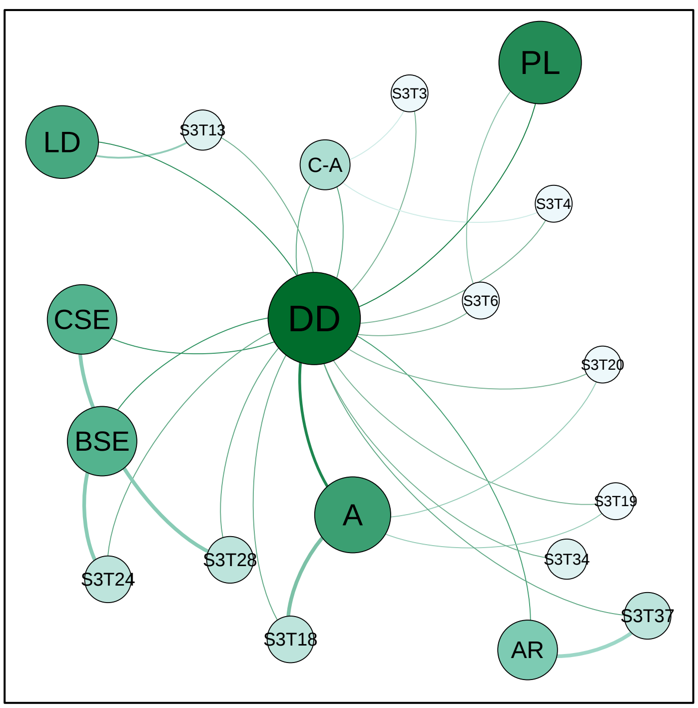


Fig. 6.40 Flow of knowledge that the developed design component is receiving in the developed design stage

The results of the technical design stage indicate that the design process component with the highest degree centrality is the technical design drawings component with 21-degree centrality. Fig. 6.41 shows the flow of knowledge that the technical design component is receiving in the technical design stage. This information is received from all the design team members of the design stage. This indicates that the technical design drawing is the most significant design process component in the technical design stage in terms of receiving amounts of information because it is connected to a lot of design team members who are delivering information to it from other design process components and design tasks.

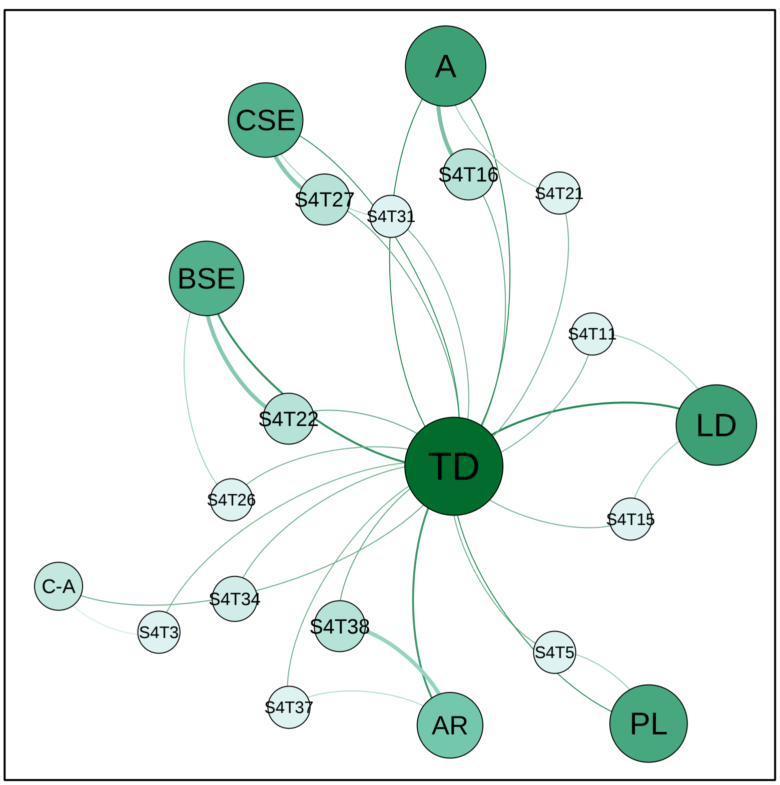


Fig. 6.41 Flow of knowledge that the technical design component is receiving in the technical design stage

6.7.3.2 The closeness centrality of design process components and the knowledge diffusion

Table 6.24 displays the results of the closeness centrality of the design process components, which measures how central the location of the design process components in knowledge diffusion in the design process stage. The results indicate that each design process component result of closeness centrality is different in each design stage, which indicates changes of location in terms of knowledge diffusion of design in each stage. This section of the research will presents the most central design process components in terms of knowledge diffusion of each design process stage.

The closeness centrality result for the design process component of the strategic definitions stage indicates that the business case and the strategic brief are the most central design process components in this stage. Fig. 6.42 shows the process of knowledge diffusion from the business case and the strategic brief design process components in the strategic definitions stage. The flow of information to the strategic brief is from all the design team members; however, to the business case, it is just from the project lead, client and client advisor.

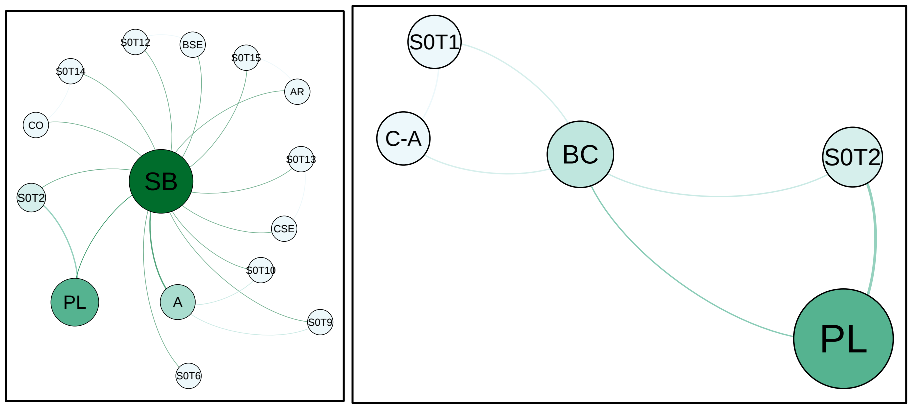


Fig. 6.42 Knowledge diffusion from the business case and the strategic brief design process components in the strategic definitions stage

The closeness centrality result for the design process component of the preparation and brief stage indicates that the feasibility studies and project programme are the most central design process components in this stage. Fig. 6.43 shows the process of knowledge diffusion from the feasibility studies and the project programme design process components in this stage. The flow of information to the feasibility studies indicates that this information is delivered from very significant design team members, who are the project lead and the architect, which means that this knowledge is central in terms of diffusion in the design process stage. The flow of information to the project programme indicates that this information is delivered from the design lead, which means that this knowledge is also central in terms of knowledge diffusion in the design process stage.

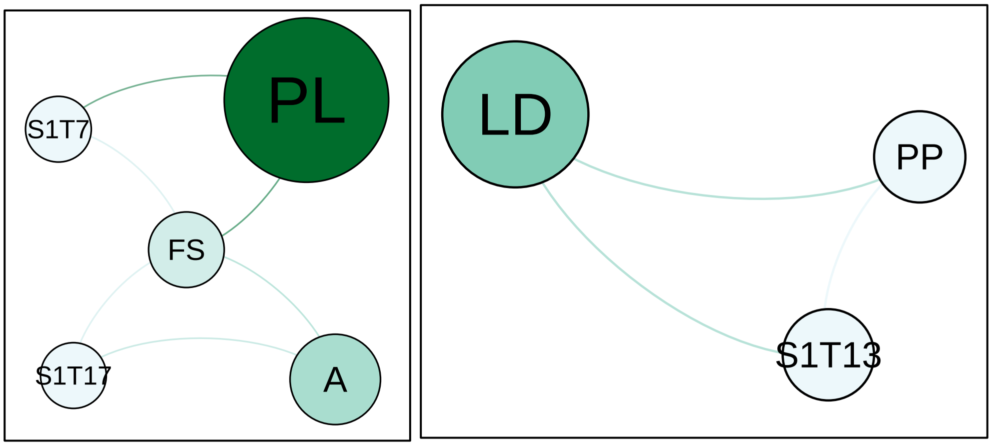


Fig. 6.43 Process of knowledge diffusion from the feasibility studies and the project program design process components in the preparation and brief stage

The closeness centrality results for the design process components of the concept design stage indicate that the stage design programme and the concept design components are the most central design process components in this stage. Fig. 6.44 shows the process of knowledge diffusion from the concept design component and the stage design programme design process components in this stage. The flow of information to the concept design drawings indicates that this information is delivered from all the design team of the stage, which makes it very central in the knowledge diffusion of the design stage. The flow of information to the stage design programme indicates that this information is delivered from all the whole design team members of the design stage, which makes it central in terms of knowledge diffusion in this design stage.

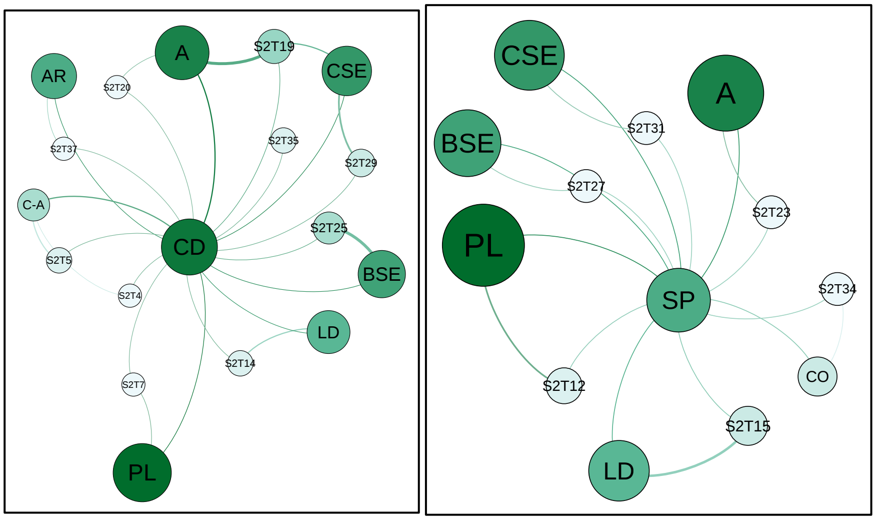


Fig. 6.44 Process of knowledge diffusion from the concept design component and the stage design programme design process components in the concept design stage

The closeness centrality results for the design process components of the developed design stage indicate that the sustainability strategies and the stage design programme components are the most central design process components in this stage. Fig. 6.44 shows the process of knowledge diffusion from the sustainability strategies and the stage design programme design process components in the developed design stage. The flow of information to the sustainability strategies indicates that this information is delivered from the architect, the additional roles, civil and structural engineer, and the building services engineer, which makes it very central in the knowledge diffusion of the design stage. The flow of information to the stage design programme indicates that this information is delivered from the whole design team, which makes it very central in terms of knowledge diffusion in the design process stage.

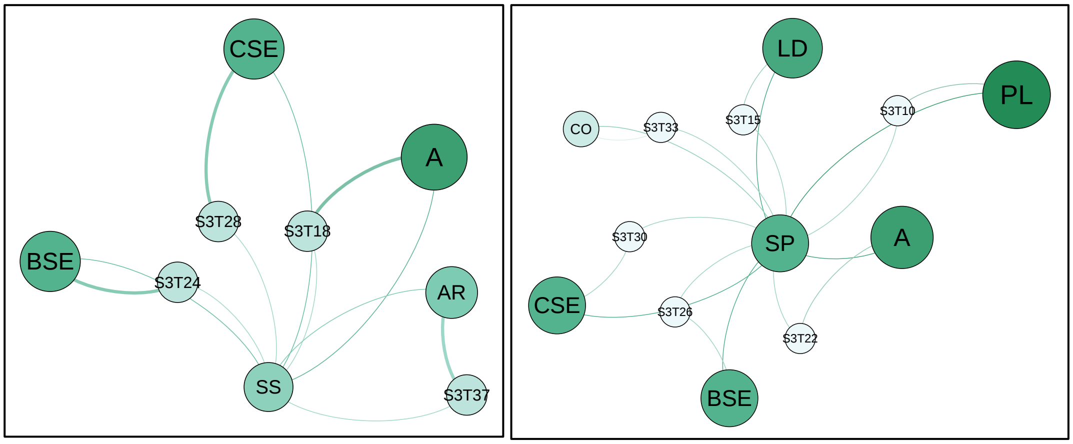


Fig. 6.44 Process knowledge diffusion from the sustainability strategies and the stage design programme design process components in the developed design stage

The closeness centrality results for the design process components of the technical design stage indicate that the technical design component and the project programme components are the most central design process components in this stage. Fig. 6.45 shows the process of knowledge diffusion from the technical design and the project programme design process components in the technical design stage. The flow of information to the technical design component indicates that this information is delivered from the whole design team, which makes it very central in the knowledge diffusion of the design stage. The flow of information to the project programme indicates that this information is delivered from the architect, additional roles, civil engineer, and building services engineer design team, which makes it very central in terms of knowledge diffusion in the design process stage.

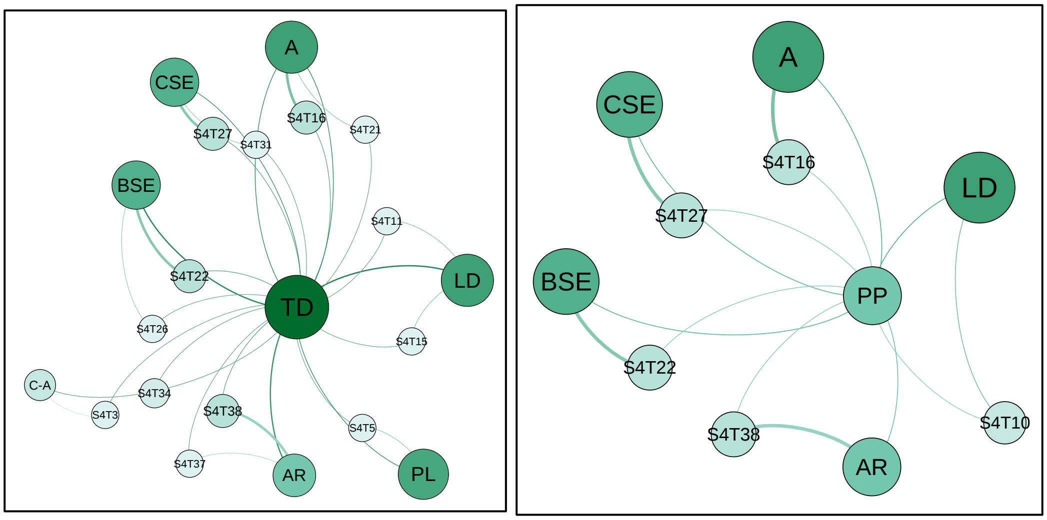


Fig. 6.45 Process of knowledge diffusion from the technical design and the project programme design process components in the technical design stage

6.7.3.3 The betweenness centrality of the design process components and knowledge diffusion

Table 6.23 displays the betweenness centrality results for the design process components, which measures the importance of the design process components in passing information through the design process stage. The results indicate the main outcome component of each design process stage has the highest betweenness centrality result; for example, in the strategic definition stage, the strategic brief has the highest score; in the preparation and brief stage, it is the initial project brief; in the concept design stage, it is the concept design drawings component; in the developed design stage, it is the developed design drawings; and in the technical design stage, the technical drawings have the highest betweenness centrality in the process components of the stage. In addition, this section will present the second highest betweenness centrality scores in the design process stages.

The results for the strategic definitions stage indicate that the second most important design process components in this stage are the business case and project program, both with betweenness centrality of 7. Disconnection of these two components will significantly affect the flow of information and design knowledge to the strategic brief. Fig. 6.46 shows the flow of information that is delivered from the project programme and the business case to the strategic brief. Fig. 6.46 indicates that the project lead is the significant design team member who delivers the information from the project programme and business case to the strategic brief.

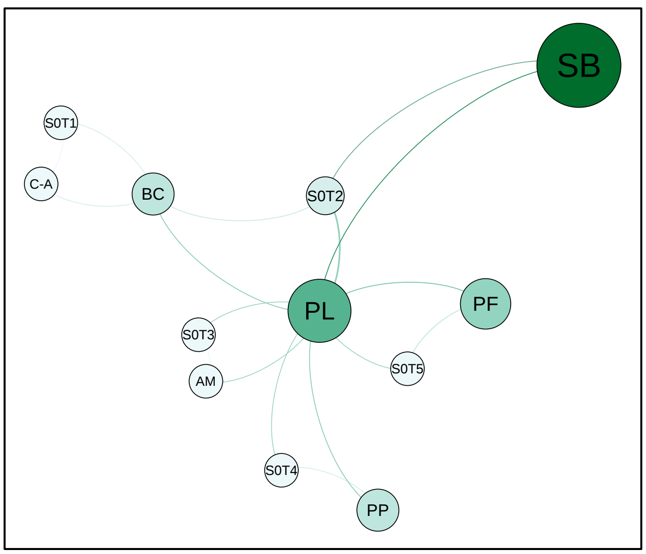


Fig. 6.46 Flow of information that is delivered from the project programme and the business case to the strategic brief

The results of the preparation and brief stage indicate that the second most important design process component in this stage is the project execution plan with betweenness centrality of 120. Disconnection of the project execution plan component will significantly affect the flow of information and design knowledge to the initial project brief. Fig. 6.47 shows the flow of information that is delivered from the project execution plan to the initial project brief. Fig. 6.47 indicates that the project lead and the all additional roles component are the significant design team members who deliver the information from the project execution plan to the initial project brief.

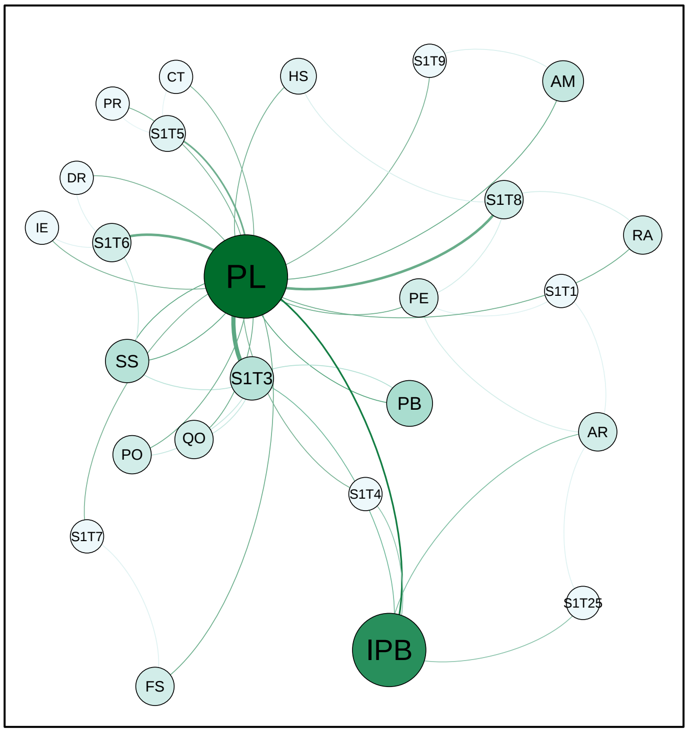


Fig. 6.47 Flow of information that is delivered from the project execution plan to the initial project brief

The results for the concept design stage indicate that the second important design process component in this stage is the final project brief with betweenness centrality of 91.6. Disconnection of the final project brief component will significantly affect the flow of information and design knowledge to the concept design drawings. Fig. 6.48 shows the flow of information that is delivered from the final project brief to the concept design drawings. Fig. 6.48 indicates that the project lead, the all additional roles component, and the client and client advisor are the significant design team members who deliver the information from the final project brief to the concept design drawings.

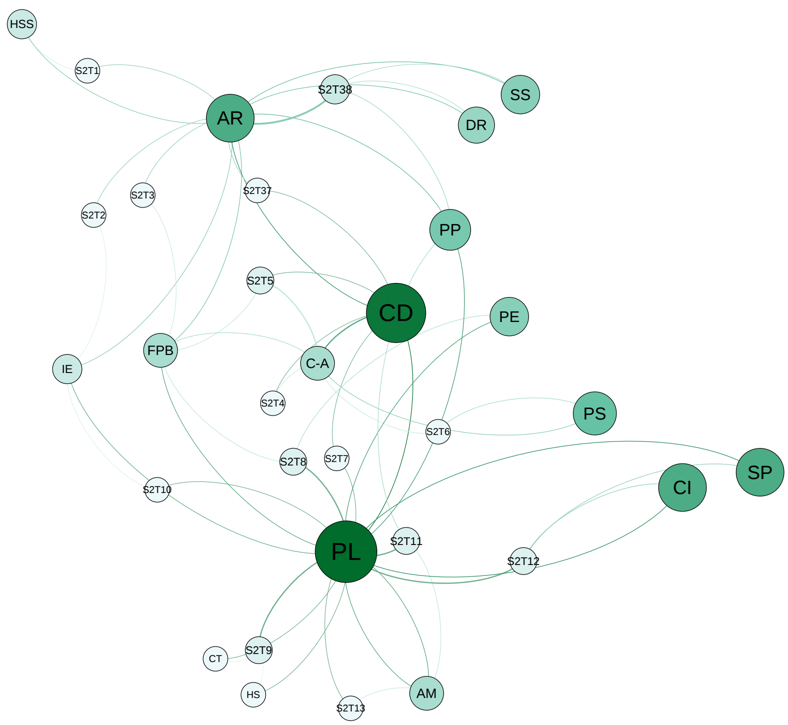


Fig. 6.48 Flow of information that is delivered from the final project brief to the concept design drawings

The results for the developed design stage indicate that the second most important design process component in this stage is the cost information with betweenness centrality of 277.76. Disconnection of the cost information component will significantly affect the flow of information and design knowledge to the developed design drawings. Fig. 6.49 shows the flow of information that is delivered from the cost information component to the developed design drawings. Fig. 6.49 indicates that the lead designer, cost consultant, civil engineer, building services engineer, and architect are the significant design team members who deliver the information from the cost information to the developed design drawings.

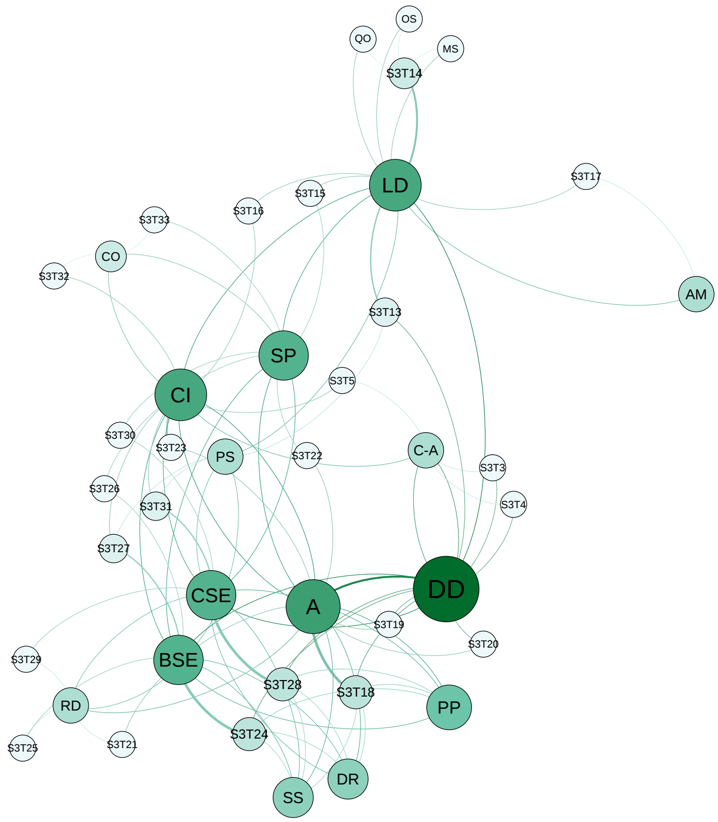
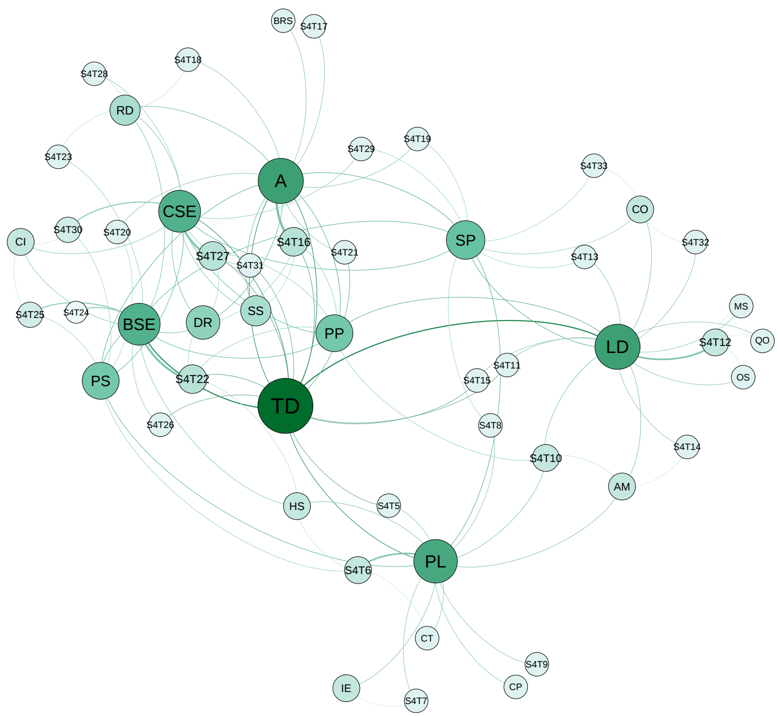


Fig. 6.49 Flow of information that is delivered from the cost information component to the developed design drawings

The results for the technical design stage indicate that the second most important design process component in this stage is the stage design programme with betweenness centrality of 238.16. The disconnection of the stage design programme component will significantly affect the flow of information and design knowledge to the technical design drawings. Fig. 6.50 shows the flow of information that is delivered from the stage design programme to the technical design drawings. Fig. 6.50 indicates that the project lead, lead designer, cost consultant, civil engineer, building services engineer, and architect are the significant design team members who deliver the information from the stage design programme to the technical design drawings.



The Fig. 6.50 Flow of information that is delivered from the stage design programme to the technical design drawings

6.8 Conclusion

This chapter of the research has uncovered very significant aspects of building design complexity, which is the complexity of the building design process. The research has used the RIBA plan of work as a case study to uncover the complexity of the building design process in terms of knowledge diffusion and information flow. In addition, the chapter has presented the three aspects of the building design process based on the RIBA plan of work. Moreover, the chapter has presented five-design structure matrix for each of the five design process stages that indicate the interactions of the design tasks, team and components of the design stage. In addition, the chapter has presented the typological characteristics of the five design process stages; each typology presents a network of the design process stage with its typological finding. Additionally, the chapter has presented an assessment of the building design process stages in terms of knowledge diffusion and information flow by using the centrality measures. The use of centrality measures such as degree, closeness and betweenness centrality indicated the significant components, team members and tasks that are in control of the information flow and knowledge diffusion in the design process stage.

CHAPTER 7: THE TYPOLOGICAL CHARACTERISTICS AND ASSESSMENT OF RESILIENCE OF ARCHITECTURAL DESIGN

7.1. Introduction

Designing the architectural layout of a building requires several decisions that have to deal with a large amount of information concerning the architectural spaces and circulation spaces. This chapter of the research will uncover one of the significant aspects that increase the complexity of building design using a case study of King Faisal Specialist Hospital & Research Centre building in Riyadh, Saudi Arabia, as a case study to model the interactions between the architectural spaces applying the method used in Chapter 4 on the theoretical framework. In addition, this complexity of interactions between these architectural spaces forms a complexity, which needs to be assessed in terms of its resilience to functionality of the architectural spaces and the circulation resilience to fire, which are the significant phenomena in terms of designing a building's architectural layout. Studying and modelling the interaction between the building architectural layouts can be looked at from a complexity science point of view in order to enhance the efficiency of the functionality of the building's architectural design. The main goal of this chapter is to model the complex interactions between the buildings architectural spaces using a new modelling approach, which are network modelling. This modelling will result in a model of connectivity between the building's architectural spaces that can be analysed and investigated from three approaches, which are the descriptive analysis of the building's architectural design, the uncovering of the typological characteristics of the architectural design network, and the analysis and the assessment of the building's architectural design in terms of the significant factors of the architectural design, which are the functionality of the building layout, the functionality of the circulation spaces in terms of fire escapes, and the assessment of the way finding in the building layout design.

7.2. Descriptive analysis of the building's architectural design

The BEEAH, planners, and architects, and engineers design the architectural design of the building, and the building is 20 floors high with two basement floors. The basements floors are used for parking and storage. The first two floors are used as reception areas and for basic functions of the building. The third, fourth and fifth floors are used for dining and shopping areas. The sixth floor is the services floor and from the seventh floor to the nineteenth floor are office spaces. Fig. 7.1 shows how the floors are used. The building floor is a rectangular shape and it consists of four concrete cores that contain the building's vertical circulation, which are the elevators and the stairs. The circulation spaces around the concrete cores consist of corridors that link the floor spaces in a rectangular-shaped of circulation flow. Fig. 7.2 indicates the use of spaces, circulation spaces, and concrete cores on the floors of the building.

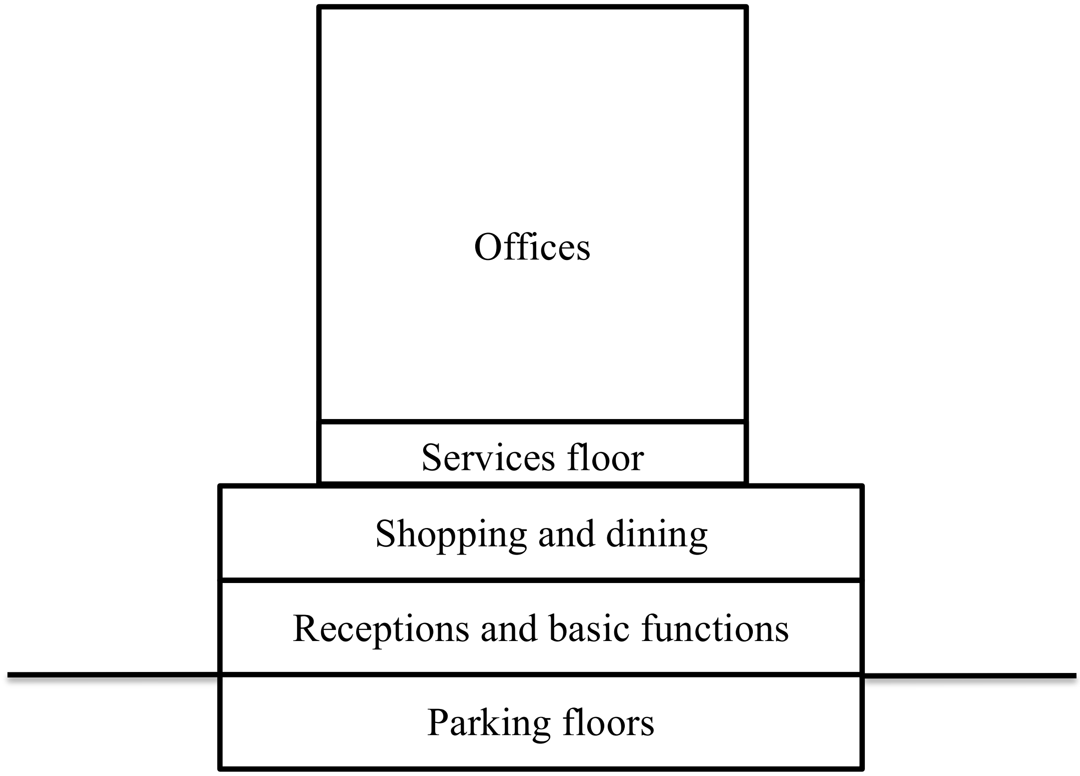


Fig. 7.1 Use of the floors of the building case study

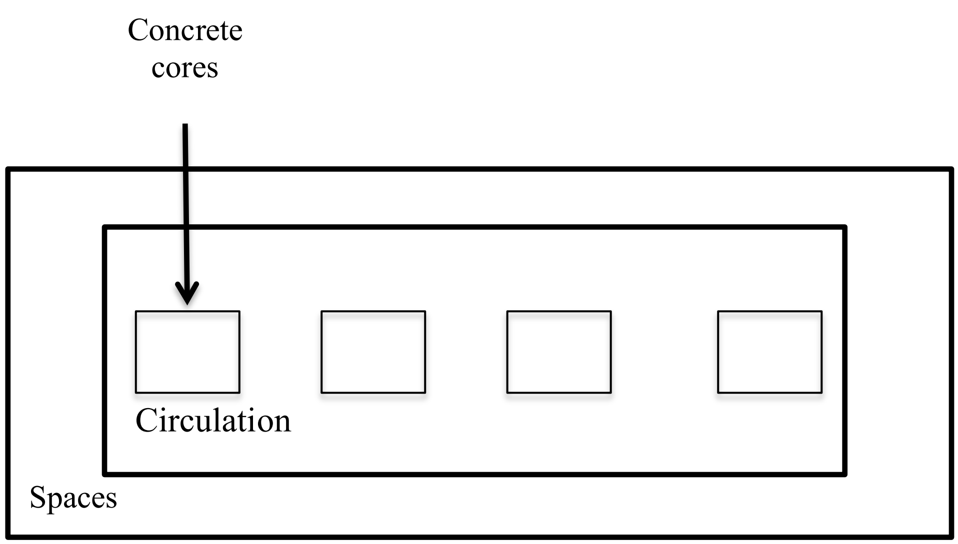


Fig. 7.2 Use of spaces, circulation spaces, and concrete cores on the building floors

This research models two significant aspects of architectural design, which are the circulation flow of the floors, and the connectivity of the architectural spaces. The components of the modelling are indicated in the theoretical model in Chapter 4; they are the architectural spaces, the circulation spaces, the stairs and the elevators.

7.3 The definition of the nodes of the networks

This section of the research will present the definition of the nodes of each system of the building, which are the nodes of the architectural, structural, envelope, HVAC, power, and lighting systems. Table 7.1 presents the content of the nodes of each of the six building systems, while he table 7.2 presents the definitions for the nodes of the building systems' components.

Table 7.1 Content of the nodes of each of the building systems

The building systems	The nodes' content	Example
Architectural	Floor level-room code- the number of rooms	F1SR1
Structural	Floor level- the structural component code	F1CA1
Envelope	Floor level- the window type- the window elevation	F1W1AW
HVAC	Floor Level- type of duct- number of ducts	F1DUCT1
Power	Floor level-Power line Number-Receptacle number	F1PL1REC1
Lighting	Floor Level- Lighting Line- Lighting fixture	F1LL1LF1

Table 7.2 Definition of the building systems nodes

B1	Basement 1	BTQ	Boutique
B2	Basement 2	SMK	Smoking area
F1	First Floor	SALS	Ladies' salon
F2	Second Floor	BOCR	Body care
F3	Third Floor	LUBD	Laundry
F4	Fourth Floor	PHA	Pharmacy
F5	Fifth Floor	GIFS	Gift shop
F6	Sixth Floor	ELES	Electrical shop
F7	Seventh Floor	MNAC	Men's accessories
F8	Eighth Floor	CARPS	Carpet shop
F9	Ninth Floor	TERR	Terrace
F10	Tenth Floor	DSHW	Dish washer
F11	Eleventh Floor	CHM	Chemical
F12	Twelfth Floor	UTI	Utilities
F13	Thirteenth Floor	CO	Control
F14	Fourteenth Floor	STAL	Stall
F15	Fifteenth Floor	FOD	Food area
F16	Sixteenth Floor	COK	Cookies shop
F17	Seventeenth Floor	CHIL	Children's zone
F18	Eighteenth Floor	DIN	Family dining hall
F19	Nineteenth Floor	ICE	Ice cream
F20	Twentieth Floor	CON	Corn shop
SR	Service area	MDIN	Men's dining room
CM	Communication	SOP	Supervisor
WMG	Waste manager	CORD	Coordinator
TO	Toilets	ASMG	Assistant manger
PM	Project manager	ACUN	Accountant
PLN	Main Panel	FIL	Filling room
SPLN	Sub Panel	REPR	Representative
SG	Storage	INTMG	Interior manger
HVC	Heating and ventilation air-conditioner	INSUM	Insurance manager
SF	Stuff Room	STC	STC
LO	Lounge	SHP	Shop
G	Generator	GOVS	Governmental service
OFF	Office	TRVA	Travel agency
LK	Lockers	DIRC	Director
LV	Low Voltage	SECR	Secretary
TRA	Trans	METR	Meeting room
WA	Waiting area	BUSM	Business manger

RP	Reception	COOR	Esc coordinator
ESC	Escalator	PHA	Pharmacy
CO	Control and Monitors	MANT	Maintenance room
DEP	Deposit Room	METR	Meeting room
DAT	Data Room	CONR	Conference room
ACH	Archive Room	SITR	Sitting area
BUS	Business Room	C	Column
COF	Coffee Room	CA	Column on Axis A
BNK	Bank	CB	Column on Axis B
GAR	Garbage Room	CC	Column on Axis C
KIT	Kitchen	CD	Column on Axis D
HAL	Hall	CE	Column on Axis E
MPR	Men's prayer room	CF	Column on Axis F
LPR	Ladies' prayer room	SP	Floor slabs
GER	Grease inter	CWA	Concrete walls
ABL	Ablution	CCO	Concrete cores
LBY	Lobby	S	Stairs
BKS	Book Store	W	Windows
KDS	Kids' store	W1AW	Windows on the north elevation
OPT	Optical shop	W1BW	Windows on the east elevation
BARB	Barber's shop	W1CW	Windows on the west elevation
PHS	Phone store	W1DW	Windows on the south elevation
ANQS	Antiques shop	DUCT	Duct
CMPS	Computer shop	RDUCT	Return duct
MOBS	Mobile shop	PL	Power line
SPTS	Sports shop	REC	Receptacle
LADAS	Ladies' accessories	LL	Lighting Line
BTQ	Boutique	LF	Lighting Fixture

7.4 The process of extracting the nodes from the case study to the networks

The process of extracting the network nodes to the building case study consists of four steps. First, listing the architectural spaces and the corridors on the floor plan, as shown in Fig. 7.3 relating to the floor plan for the eighth floor of the building; this step lists the architectural spaces and corridors from the floor plan. Second, generating a design structure matrix that indicates the interactions between the architectural spaces and the interactions of the corridors of the floor plan, as shown in Fig. 7.4 Third, listing the interactions of the design structure matrix, as shown in the Fig. 7.5. Fourth, importing the list of interactions into Gephi to generate the networks.

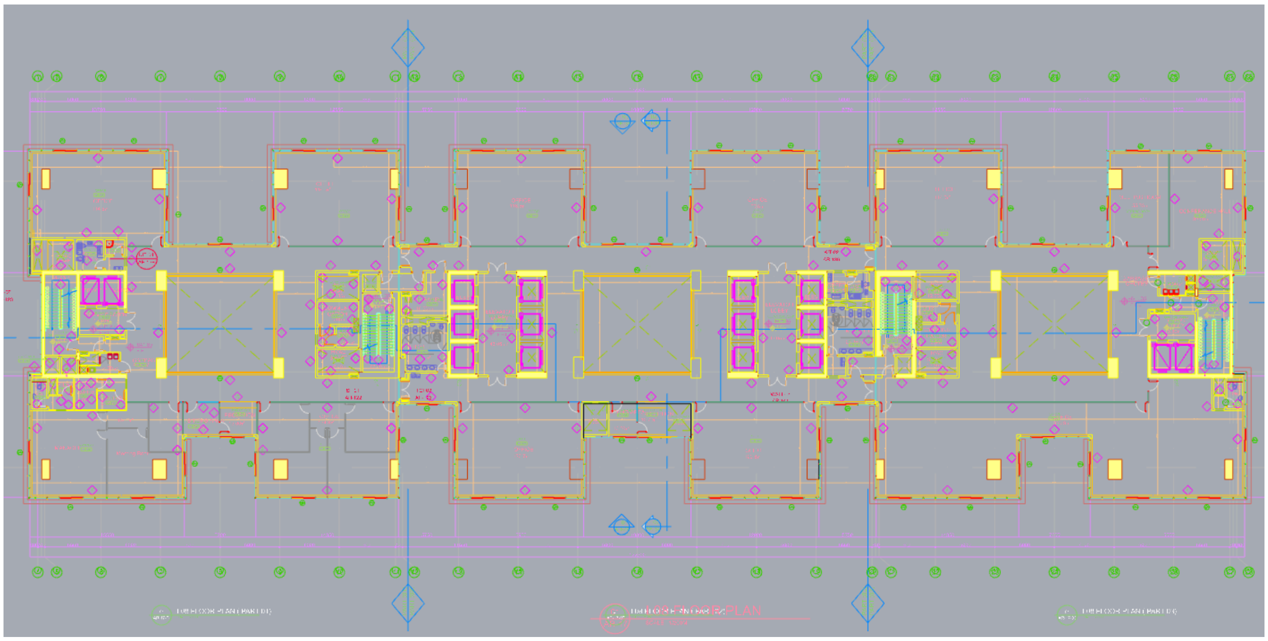


Fig. 7.3 Architectural spaces and corridors on the eighth floor of the building

	F8LPR1	F8OFFC1	F8OFFC2	F8OFFC3	F8OFFC4	F8OFFC5	F8OFFC6	F8OFFC7	F8METR1	F8CONR1	F8MANG1	F8SITR1	F8RP1	F8HVC1	F8SITR2	F8RP2	F8HVC2	F8GAR1	F8SR1	F8HVC3	F8HVC4	F8CM1	F8SPN1	F8HVC5	F8PLN	F8TO1	F8COF1	F8KIT1	F8TO2	F8HVC6	F8CM2	F8SPN2	F8HVC7	F8GAR2	F8SR2	F8HVC8	F8HVC9	F8TO3	F8HVAC10	F8SR1	F8CIRCU1	F8CIRCU2	F8CIRCU3	F8CIRCU4	F8CIRCU5	F8CIRCU6	F8CIRCU7	F8CIRCU8
F8LPR1														x																											x							
F8OFFC1																																									x							
F8OFFC2																																									x							
F8OFFC3																																									x							
F8OFFC4																																									x							
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F8OFFC6															x																											x						
F8OFFC7																																										x						
F8METR1						x																																				x						
F8CONR1									x																														x		x	x						
F8MANG1								x																																		x						
F8SITR1											x																															x						
F8RP1												x																														x						
F8HVC1																																											x					
F8SITR2																x																										x						
F8RP2								x																																		x						
F8HVC2																																											x					
F8GAR1																			x	x																							x					
F8SR1																																											x					
F8HVC3																	x																											x				
F8HVC4																																												x				
F8CM1																					x																							x				
F8SPN1																						x		x																				x				
F8HVC5																																															x	
F8PLN																										x															x							
F8TO1																																										x						
F8COF1																													x																		x	
F8KIT1																											x		x																		x	
F8TO2																																										x						
F8HVC6																																																x
F8CM2																							x																									x
F8SPN2																														x																		x
F8HVC7																															x																	x
F8GAR2																																				x												x
F8SR2																																		x			x											x
F8HVC8																																																x
F8HVC9																																				x												x
F8TO3											x																															x						
F8HVAC10																																																x
F8SR1																																																x
F8CIRCU1																																											x	x	x	x	x	x
F8CIRCU2																																											x	x	x	x	x	x
F8CIRCU3																																																
F8CIRCU4																																																
F8CIRCU5																																																
F8CIRCU6																																																
F8CIRCU7																																																
F8CIRCU8																																																

Fig. 7.4 Design structure matrix of the eighth floor of the building

Node 1	Nodes 2	Node 1	Node 2	Node 1	Node 2
F8LPR1	F8CIRCU1	F8TO2	F8CIRCU2	F8SPN1	F8HVC5
F8OFFC1	F8CIRCU1	F8HVC6	F8CIRCU8	F8PLN	F8TO1
F8OFFC2	F8CIRCU1	F8CM2	F8CIRCU8	F8COF1	F8TO2
F8OFFC3	F8CIRCU1	F8SPN1	F8CIRCU8	F8KIT1	F8COF1
F8OFFC4	F8CIRCU1	F8HVC7	F8CIRCU8	F8KIT1	F8TO2
F8OFFC5	F8CIRCU2	F8GAR2	F8CIRCU8	F8CM2	F8SPN1
F8OFFC6	F8CIRCU2	F8SR2	F8CIRCU8	F8SPN2	F8HVC6
F8OFFC7	F8CIRCU2	F8HVC8	F8CIRCU8	F8HVC7	F8CM2
F8METR1	F8CIRCU2	F8HVC9	F8CIRCU8	F8GAR2	F8HVC8
F8CONR1	F8CIRCU1	F8TO3	F8CIRCU2	F8SR2	F8GAR2
F8MANG1	F8CIRCU2	F8HVAC10	F8CIRCU8	F8SR2	F8HVC9
F8SITR1	F8CIRCU2	F8SR1	F8CIRCU8	F8HVC9	F8HVC8
F8RP1	F8CIRCU2	F8LPR1	F8HVC1	F8TO3	F8MANG1
F8HVC1	F8CIRCU3	F8OFFC5	F8RP1	F8CIRCU1	F8CIRCU3
F8SITR2	F8CIRCU2	F8OFFC6	F8SITR2	F8CIRCU1	F8CIRCU4
F8RP2	F8CIRCU2	F8METR1	F8OFFC5	F8CIRCU1	F8CIRCU5
F8HVC2	F8CIRCU3	F8CONR1	F8METR1	F8CIRCU1	F8CIRCU6
F8GAR1	F8CIRCU3	F8CONR1	F8HVAC10	F8CIRCU1	F8CIRCU7
F8SR1	F8CIRCU3	F8MANG1	F8OFFC7	F8CIRCU1	F8CIRCU8
F8HVC3	F8CIRCU4	F8SITR1	F8MANG1	F8CIRCU2	F8CIRCU3
F8HVC4	F8CIRCU4	F8RP1	F8SITR1	F8CIRCU2	F8CIRCU4
F8CM1	F8CIRCU4	F8SITR2	F8RP2	F8CIRCU2	F8CIRCU5
F8SPN1	F8CIRCU4	F8RP2	F8OFFC7	F8CIRCU2	F8CIRCU6
F8HVC5	F8CIRCU7	F8GAR1	F8HVC3	F8CIRCU2	F8CIRCU7
F8PLN	F8CIRCU1	F8GAR1	F8SR1	F8CIRCU2	F8CIRCU8
F8TO1	F8CIRCU2	F8HVC3	F8HVC2		
F8COF1	F8CIRCU7	F8CM1	F8HVC4		
F8KIT1	F8CIRCU7	F8SPN1	F8CM1		

Fig. 7.5 The interactions list from the design structure matrix of the eighth floor of the building

7.5. Network centrality measures of the building architectural design

The centrality measures are very significant aspects of network analysis because they help to determine the significant architectural spaces in terms of their network connectivity; they are the most influential nodes in the network of the building's architectural layout design. In this research, the centrality measures are used to enhance the ability to uncover the complex architectural design of spaces in the building and to assess the resilience of these spaces to certain phenomena such as functional relationships, flow of circulation and fire escape, way finding of spaces, productivity of users, spaces' natural lighting verses artificial lighting, etc. The centrality measures that are going to be calculated using Gephi in this research are the degree centrality, closeness centrality, and betweenness centrality. The following subsections define the centrality measures that are going to be used in this research as well as the interpretation of these measures in terms of architecture.

7.5.1 Degree centrality of the building's architectural layout design

This is defined as the number of edges that are connected to the node in a network. Table 7.3 indicates the interpretation of the degree centrality measure to the building system network.

Table 7.3 Interpretation of the degree centrality measure to the building's architectural layout network

The node in the network	The interpretation of the degree centrality in terms of connectivity in building systems design
Architectural system	The degree centrality of the architectural system's components such as circulation spaces, spaces, stairs, and elevators indicates the number of components that interact with it. The degree centrality of an architectural space is the number of components that are connected to it. This number indicates the importance of these components in designing the building's architectural layout. As the degree centrality of an architectural space increases it indicates that the space is in an important position in the building circulation design network, as well as the functionality of the space.

7.5.2 Closeness centrality of the building's architectural layout

The closeness centrality of a node measures the centrality of that node in the architectural design network. Closeness centrality measures the average distance of a node to all nodes in the network and the more central the node in the network, the lower its distance to all other nodes in the network. Table 7.4 indicates the interpretation of the closeness centrality measure to the building's architectural design network.

Table 7.4 Interpretation of the closeness centrality measure to the building's architectural design network

The node in the network	The interpretation of the closeness centrality in terms of connectivity in building systems design
Architectural system	The closeness centrality of the architectural system components such as architectural spaces and circulation spaces, elevators and stairs indicates the average distance of the component to all nodes in the network. It indicates how central the component is in the architectural network, which indicates its importance in terms of connectivity in the network.

7.5.3 Betweenness centrality in the building's architectural layout

Betweenness centrality measures the centrality of a node in connecting other nodes in the network. It measures how often the node is positioned in the shortest path between two nodes in the network. Betweenness centrality quantifies the number of times a node acts as a bridge to connect two nodes through the shortest path between them. This measurement indicates the importance of the nodes in the network in terms of passing information through the network. The node with a higher value of betweenness centrality in a network is the most important node in the network flow. Table 7.5 indicates the interpretation of the betweenness centrality measure in the building's architectural design network.

Table 7.5 Interpretation of the betweenness centrality measure in the building's architectural design network

The node in the network	The interpretation of the betweenness centrality in terms of connectivity in building systems design
Architectural system	The betweenness centrality of the architectural system components such as architectural spaces and circulation spaces, elevators and stairs indicates the number of times the component works as a bridge to connect two components through the shortest path in the network. The betweenness centrality indicates the importance of the component in terms of connecting the components in the network.

7.6. Network of architectural spaces' interactions and flow of circulation

The rationale and methodology for modelling the interaction between spaces is presented in chapter 5. An architectural system is defined in this research as a network that connects the architectural spaces to each other, which is what architects design as the layout of a building. The components of the architectural system are the architectural spaces and the circulation spaces as well as the vertical circulation, which consists of elevators and stairs. The theoretical framework in Chapter 4 indicates the methods of modelling the interactions between the architectural system components as a network. Each floor of the case study building consists of one circulation space; these spaces are connected to each other though the vertical circulation spaces and the stairs. Fig. 7.6 was modelled using Gephi; it shows the typology of the building's architectural spaces' interactions as well as the circulation flow in the building.

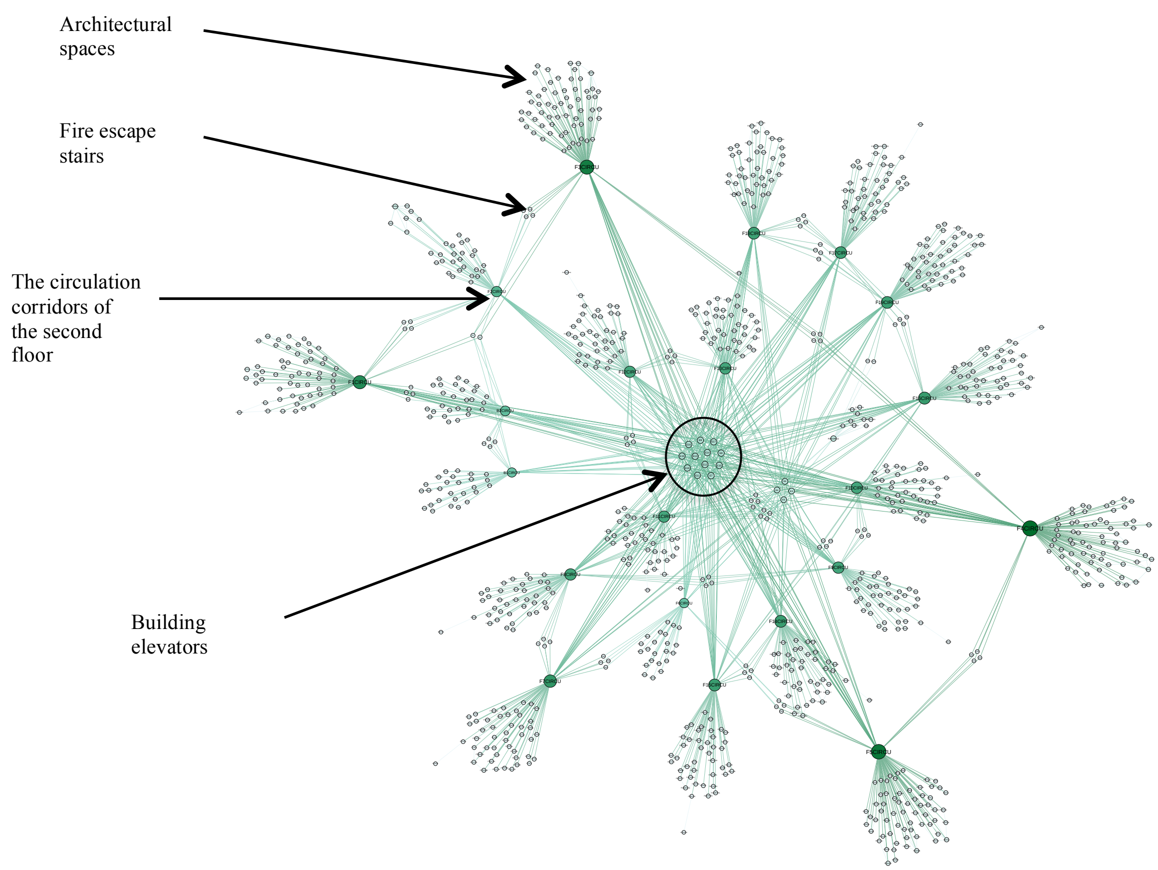

Fig. 7.6 Typology of the building's architectural spaces' interactions as well as the circulation flow in the building

The architectural network in Fig. 7.4, which was modelled using Gephi, consists of 1022 nodes and 2101 edges. The nodes represent the architectural spaces, which are the reception spaces; the shopping spaces, the office spaces and the services spaces, and the edges represent the interactions between the spaces. Generally, the architectural network consists of 22 clusters; each cluster is a floor plan that has a circulation space and spaces that are connected to the circulation space. In addition, there is a central cluster, which consists of 16 elevators that are connected to the building's 22 circulation spaces. The larger the node, the higher degree centrality it has, and the more it interacts in the network. As Fig. 7.4 shows, the 22 circulation spaces are the larger nodes in the network because they link all the spaces in the floor to each other. For example, Fig. 7.7 indicates the circulation of the second floor and the third floor and the connecting nodes between them, which are the stairs F2S1, F2S2, F2S3, and F2S4. In addition, the 16 elevators are connected to the F2CIRCU and F3CIRCU, which works as a connection between the two circulation spaces. The F2CIRCU degree centrality is 54, which indicates that the circulation space of the second floor is connected to 54 components of the architectural system. These components are the four stairs that rise from the first floor, four stairs that lead to the third floor, 16 elevators, and 30 spaces on the second floor.

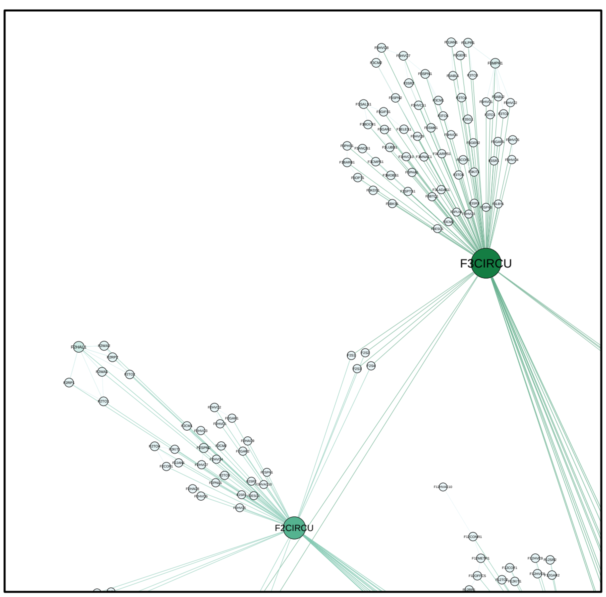

Fig. 7.7 Circulation of the second floor and the third floor and the connecting nodes between them, which are the stairs F2S1, F2S2, F2S3, and F2S4

7.5. General characteristics of centrality measures of the architectural design network

Table 7.6 indicates the general characteristics of the degree centrality, closeness centrality, and betweenness centrality of the nodes in the architectural network. The average degree centrality of the nodes in the network is 4.11. The result indicates that the average interactions between the architectural system components are 4.11, the average closeness centrality – which indicates the average shortest path between nodes in the architectural components network – is 11.44, and the average betweenness centrality between nodes in the network – which indicates the average times the nodes acts as a bridge to connect other nodes in the shortest path – is 770.48. In addition, the highest degree centrality node in the network is F4CIRCU, which is the circulation space of the fourth floor, with degree centrality of 92 compared to the average, which are 4.11. This indicates that there is a large number of nodes with view interactions and view number of nodes that control the connectivity of this network, which are the circulation spaces. The highest closeness centrality node in the network is 22, which is the result of a large number of spaces; however, the lowest numbers are for the elevators, which are the most central components in the network because they are connected to all circulation spaces; closeness centrality is 1.8. A large number of the nodes in the network resulted in 0 betweenness centrality, which indicates that these nodes are not located in the shortest path between nodes. These nodes are mainly the clusters of the architectural spaces that are linked to the circulation spaces. However, the circulation spaces and the stairs have high betweenness centrality; the maximum betweenness centrality is the circulation space of the eighth floor, F8CIRCU. The standard deviation of the degree centrality is 9.3, which is an indication of a large number of nodes with low degree centrality compared to the higher degree centrality and for the closeness centrality resulted in 6.08 and betweenness centrality of 3309.18. The sum results indicate how large the network is; as the number of nodes increases, the possible results increase; for example, 4202-degree centrality is possible in this architectural network as an average degree centrality.

Table 7.6 General characteristics of the centrality measures of the nodes in the architectural network

	Centrality measures		
	Degree centrality	Closeness centrality	Betweenness centrality
MEANS	4.11	11.44	770.48
SD	9.30	6.08	3309.18
SUM	4202	11695.21	787430
VAR	86.53	37.05	10950675
MIN	1	0	0
MAX	92	22	29284

7.6.1 Centrality measures of the architectural system's significant components

This section of the research will present the centrality measures of the circulation spaces of the building. The results were calculated using Gephi. The centrality measures applied are the degree centrality, the closeness centrality, and the betweenness centrality. The nodes that will be investigated in the network are the circulation spaces in each floor of the building because they are the most important nodes in terms of connecting the network and they have the higher degree centrality in the network. Table 7.7 indicates the centrality measure results for the circulation spaces of the building.

The degree centrality of the circulation spaces' nodes represents the number of spaces that are connected to them as well as the elevators and the stairs. The results indicate that F4CIRCU, which is the fourth floor circulation space, has the highest degree centrality of the circulation spaces in the building, and F20CIRCU, which is the twentieth floor circulation space, has the lower degree centrality of the circulation spaces. The degree centrality measure of circulation spaces indicates the circulation flow in the building. For example, the degree centrality of F1CIRCU is 76 and for F2CIRCU it is 54; both circulation spaces are connected to four fire stairs and 16 elevators. This indicates that F1CIRCU has 56 spaces that are connected to four fire exits. However, F2CIRCU has 34 spaces that are connected to four fire exits.

The closeness centrality of the circulation spaces indicates the circulation nodes that are central in the graph in terms of their closeness to all nodes in the networks. The results indicate a pattern of lower closeness to the higher floor, and the closeness increases, as the floors get closer to the first floor and basements. This indicates that the flow of circulation in the first floors is higher than in the lower floors of the building

The results of betweenness centrality indicate the number of times that the circulation space works as a bridge to connect two nodes in the network through the shortest path. The results indicate that there is a pattern between the degree centrality of the circulation spaces and the betweenness centrality of the node: as the number of degrees increase, the betweenness also increases. The number of degrees indicates the number of spaces that are connected to the circulation spaces: as the number of spaces connected to a circulation space increases, it increases the number of times this circulation spaces works as a bridge to connect other circulation spaces to each other. In terms of designing a building layout, the larger the circulation space, the more important it is in terms of connecting other spaces that are linked to other circulation spaces.

	Centrality measures		
Architectural space	**Degree centrality**	**Closeness centrality**	**Betweenness centrality**
B2CIRCU	49	20.2	5956
F1CIRCU	76	19.2	11266
F2CIRCU	54	18.2	14006
F3CIRCU	83	17.2	19003
F4CIRCU	92	16.2	23744
F5CIRCU	87	15.2	27364
F6CIRCU	46	14.2	27434
F7CIRCU	70	13.2	28859
F8CIRCU	62	12.2	29284
F9CIRCU	62	11.2	29269
F10CIRCU	62	10.2	28814
F11CIRCU	61	9.2	27874
F12CIRCU	61	8.2	26464
F13CIRCU	62	7.2	24704
F14CIRCU	66	6.2	22624
F15CIRCU	66	5.2	20064
F16CIRCU	67	4.2	17044
F17CIRCU	65	3.2	13504
F18CIRCU	65	2.2	9484
F19CIRCU	65	1.2	5016
F20CIRCU	15	0	0

Table 7.7 Centrality measures results for the building's circulation spaces

7.7. Assessment of the architectural design's significant factors

This section of the research will investigate and assess the significant factors in designing the building's architectural layout. The first factor is the design efficiency of the building's layout in terms of the functional relationships between spaces. There are several methods used in the literature, such as design structure matrix and bubble diagram, to assess the relationship between architectural spaces, which helps to generate the form of the building layout. The second factor is the assessment of the flow of circulation in the building and the assessment of the building's circulation flow in terms of fire escape. The third factor that will be assessed in this section is the ability of building users to way find in the building's circulation.

7.7.1 Assessment of the building design layout's functionality using centrality measures

The architectural space is the space that is required in the architectural programme to be designed in the building. Each architectural space has design requirements, either external requirements or internal requirements. Those spaces form the spatial system of the building. This spatial system consists of the building spaces and the circulation spaces that link those spaces together for building users to move through the building spaces. In addition, designing the layout of the architectural spaces of the building requires understanding of the relations between the architectural spaces and determining the design of the layout and the location of the spaces in the layout. The spaces that that are strongly connected need to interact and be close to each other. This section of the research will look at the layout of the building's architectural spaces to determine the spaces that have strong relations. One of the methods architects use to design the layout of a building is bubble diagrams. According to WiseGeek (2014), a bubble diagram is a diagram that represents visual information; a bubble represents each piece of information. This type of diagram can be used to represent a variety planning and design information. There are several programs and software packages that can represent information in the form of bubble diagrams. These programs are used to model the relations between varieties of architectural spaces' relations in order to help the architects to determine the optimal design for the layout of the building, which can achieve the functional requirements of the spaces. In addition, WiseGeek (2014) gives an example that architects use bubble diagrams of architectural spaces for clients, which helps to discuss a variety of architectural solutions to the layout with the client, as well as the bubble diagrams help the architect to start developing the floor plans of the building in a precise way. The bubble diagram of a building's floor plan can represent the flow of a space, and provide information about the size of the rooms and the relations between the spaces.

This section of the research will assess the strength of functional relationships between the case study spaces using the method of modelling the interactions between the spaces as networks and applying the centrality measures to indicate the importance of the architectural spaces and the functional relations between them.

The use of network modelling will present the interactions of the building spaces as a bubble diagram; however, this research will add further analysis to the networks generated to enhance the efficiency of generating the building layout design. The use of centrality measures will significantly enhance the ability to understand the strength of the relations between the building's spaces, which significantly helps to generate a good design for the building's architectural layout.

This section of the research will model the interactions of the architectural spaces of the eighth floor of the building case study. The nodes in the networks indicate architectural spaces, which are the offices spaces, the services spaces and the circulation corridors that link the spaces together, and the edges indicate a strong relationship between the architectural spaces. Fig. 7.15 shows the modelling of the interactions between architectural spaces of the eighth floor of the building case study. The network indicates that the spaces are central on the eight circulation corridors of the floor and the spaces are connected to each other in terms of their closeness to each other in the floor plan. When generating a network of the functional relationships of a building's spaces, the designers can use the centrality measures to indicate the importance of the architectural spaces and the architectural spaces that are most central in the building, so they can be taken into consideration in the design of the building's layout.

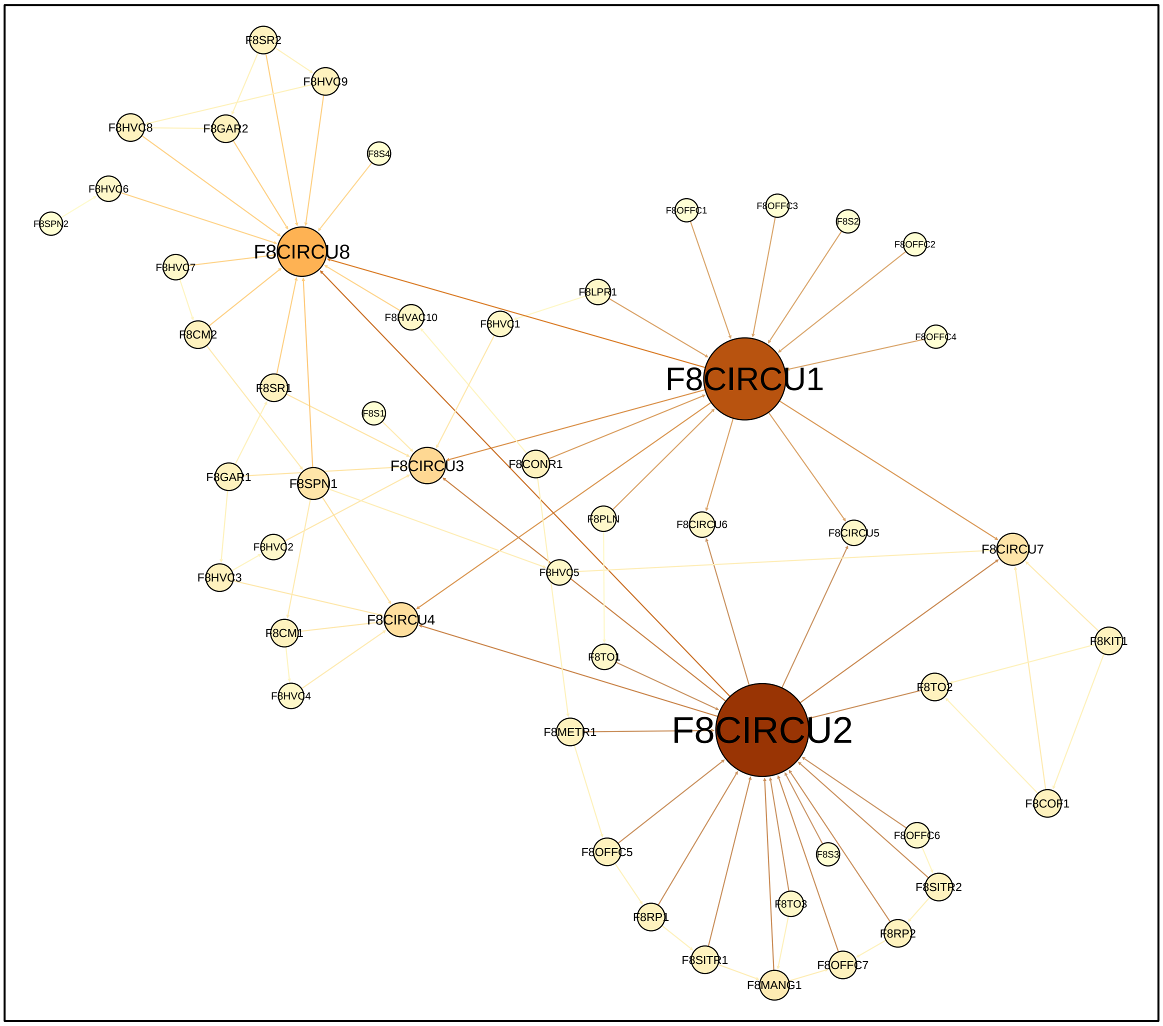

Fig.7.15 Interactions between architectural spaces of the eighth floor of the building case study.

The use of degree centrality and the importance of the space function

The increased degree centrality of a node in Fig. 7.15 indicates that the architectural space is a significant space in terms of its connectivity to the other floor spaces and to the circulation corridors. For example, Table 7.6 shows the highest degree centrality result for the architectural spaces in the eighth floor of the building. The result indicates that F8CIRCU2, which is circulation corridor number 2 on the eighth floor, is connected to 19 architectural spaces and corridors; each is connected to several spaces that are very attached to it. The next architectural space are the most important architectural space in the floor because it is functionality linked to spaces which make them very important to be taken in consideration in the initial stage of designing the layout of the building. The decrease of closeness centrality of a space indicates that the space is very central in the floor's functional relationships network. Thus, as the space's closeness centrality decreases, it indicates the importance of the space to be taken into consideration in the initial space of the design of the building layout. Table 7.8 indicates different result for the closeness centrality of the architectural space, and the circulation corridors, which indicates that the most central space is F8CIRCU2, and then the spaces with a higher degree centrality. The results indicate a strong pattern between the closeness centrality and the degree centrality of the architectural space functional relationship results.

Table 7.8 Highest results for degree centrality of the architectural spaces in the eighth floor of the building

Label	Degree	Closeness Centrality
F8CIRCU2	19	1
F8CIRCU1	14	1
F8CIRCU8	13	0
F8CIRCU3	7	0
F8CIRCU4	6	0
F8SPN1	5	1.3
F8CIRCU7	5	0
F8MANG1	4	1.75
F8OFFC5	3	2.09

Furthermore, this section of the research will highlight the strength of the relationships between the architectural spaces and the corridors of the circulation spaces. Fig. 7.16

indicates the layout design of the eighth floor of the building, which consists of eight corridors and four concrete cores, and the architectural spaces are located along the corridors. Fig. 7.17 shows the modelling of the interaction between the architectural spaces and the circulation spaces of the eighth floor of the building. The network of the eighth floor of the building consists of 56 nodes and 113 edges; the nodes represent the architectural spaces and the circulation spaces, and the edges represent the functional relationship between those spaces. Table 7.8 provides the results for the centrality measures for the circulation spaces of the eighth floor, which shows that F8CIRCU1 and F8CIRCU2 are the most important corridors on the floor because they are the longest corridors and the ones most connected to the architectural spaces. Corridor F8CIRCU1 has 28 degrees of centrality and F8CIRCU2 has 33 degrees of centrality, which indicates that they are connected to a large number of spaces. These corridors are working as paths to connect several spaces in the floor's networks. The closeness centrality of these two corridors is the highest with 1 closeness centrality, and their betweenness centrality indicates their importance in working as a bridge to connect all the architectural spaces to each other in the floor plan. Any failure of one of these corridors to connect would mean a failure of the circulation in the floor. In addition, there are six sub-corridors, all link the main two corridors to each other; these corridors work as alternatives to each other: when one is not connecting, the others will help to maintain the floor plan's circulation flow.

The goal of modelling the interactions of the functional relationships between the architectural spaces and the circulation corridors is to indicate the optical way of designing the floor plan using the method of network analysis and centrality measures. Table7.9 provides the results of the centrality measures for the architectural spaces of the eighth floor of the building. The most important space on this floor is the office space because it performs the main function of this floor as an office floor, so this section will highlight the design paths between these spaces. Fig. 7.18 indicates the connectivity between the architectural spaces and the possible shortest paths between the office spaces in the eighth floor. As shown in Fig. 7.18, the movement from one office space to another requires going through a path of circulation corridors. The spaces with strong relationships are located along the longest corridor, so it requires one corridor to reach to another space, such as the distance between F8OFF6 and F8OFF7 requires the building user to use F8CIRCU2 to reach the other space. However, some spaces require three circulation corridor paths to reach the other space, such as F8OFF4 and F8OFF6 require the user to go through two circulation corridors, which are F8CIRCU1 and the one of the sub-corridors F8CIRCU3, F8CIRCU4, F8CIRCU5, F8CIRCU6, F8CIRCU7, or F8CIRCU8, which takes the building user to F8CIRCU2, which leads to F8OFF6. As a result, modelling the circulation corridors and the architectural spaces will significantly enhance the ability to connect the architectural spaces that need to be close to each other and have very strong functional relationships.

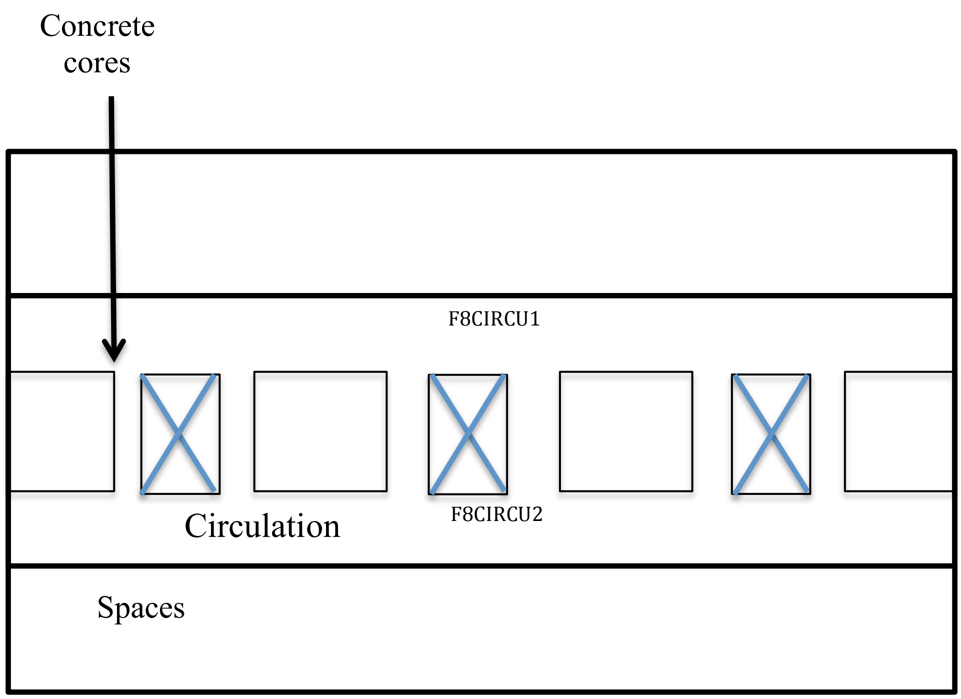

Fig. 7.16 Layout design of the eighth floor of the building

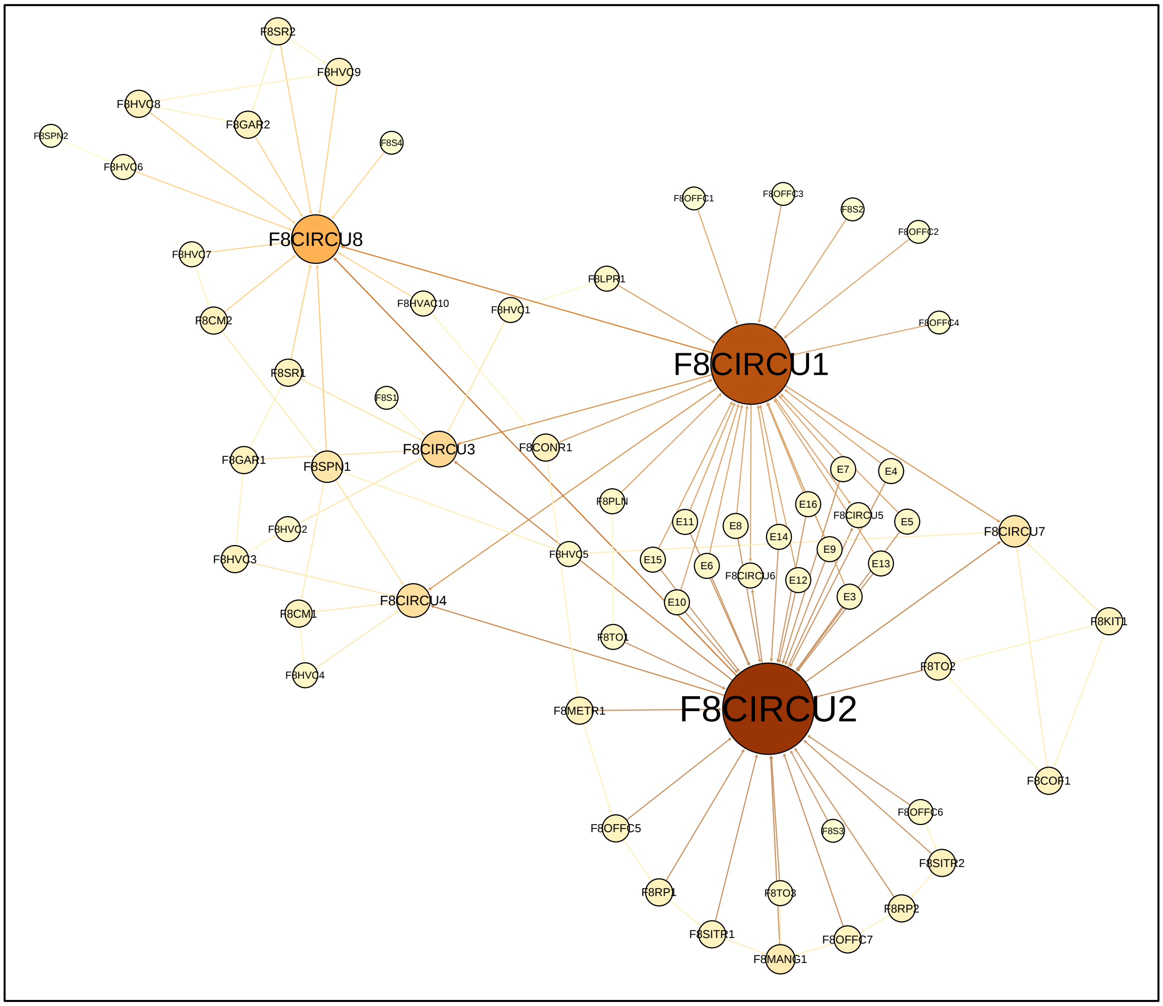

Fig. 7.17 Interaction between the architectural spaces and the circulation spaces of the eighth floor of the building

Table 7.9 Centrality measures for the circulation spaces of the eighth floor of the building

The circulation corridors	Degree centrality	Closeness Centrality	Betweenness centrality
F8CIRCU1	28	1	89
F8CIRCU2	33	1	130
F8CIRCU3	7	0	0
F8CIRCU4	6	0	0
F8CIRCU5	2	0	0
F8CIRCU6	2	0	0
F8CIRCU7	5	0	0
F8CIRCU8	13	0	0

Table.7.10 Centrality measures for the architectural spaces of the eighth floor of the building

Label	Degree	Closeness Centrality	Betweenness Centrality
F8SPN1	5.00	1.33	10.00
F8MANG1	4.00	1.75	6.00
F8OFFC5	3.00	2.09	8.00
F8OFFC7	3.00	1.86	0.00
F8METR1	3.00	2.33	6.00
F8CONR1	3.00	2.47	0.00
F8SITR1	3.00	1.78	8.00
F8RP1	3.00	1.90	9.00
F8SITR2	3.00	1.78	2.00
F8RP2	3.00	1.75	2.00
F8GAR1	3.00	1.50	0.00
F8SR1	3.00	1.00	1.00
F8HVC3	3.00	1.33	2.00
F8CM1	3.00	1.00	3.00
F8COF1	3.00	2.38	0.00
F8KIT1	3.00	2.22	0.00
F8TO2	3.00	1.86	12.00
F8CM2	3.00	2.00	6.00
F8GAR2	3.00	1.00	0.50
F8SR2	3.00	1.25	0.00
F8HVC8	3.00	1.00	0.00
F8HVC9	3.00	1.00	0.50
F8LPR1	2.00	1.75	0.00
F8OFFC6	2.00	1.90	0.00
F8HVC1	2.00	1.00	0.50
F8HVC2	2.00	1.00	1.00
F8HVC4	2.00	1.00	0.00
F8HVC5	2.00	1.00	3.00
F8PLN	2.00	1.78	0.00
F8TO1	2.00	1.86	1.00
F8HVC6	2.00	1.00	1.00
F8HVC7	2.00	2.63	0.00
F8TO3	2.00	1.78	0.00
F8HVAC10	2.00	1.00	0.50
F8OFFC1	1.00	1.86	0.00
F8OFFC2	1.00	1.86	0.00

F8OFFC3	1.00	1.86	0.00
F8OFFC4	1.00	1.86	0.00

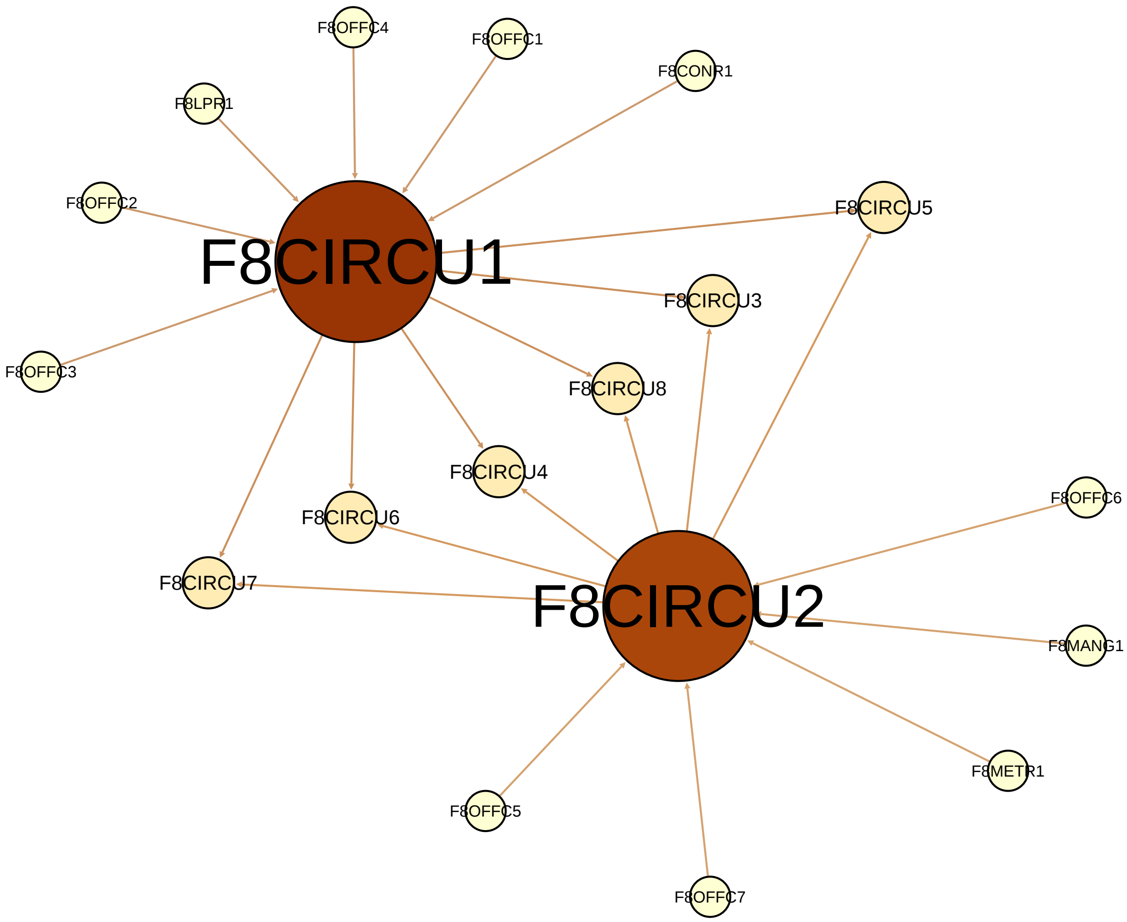

Fig. 7.18 Connectivity between the architectural spaces and the possible shortest paths between the office spaces on the eighth floor

7.7.2 Assessment of the building circulation design's resilience to fire using centrality measures

One of the most important aspects of the design of a building's architectural layout is the successful design of its circulation flow. In architecture, circulation refers to the paths that building users move through to interact with the building spaces. In addition, in this case study building the research will model the flow of circulation based on the flow of people in the building and the closeness of the architectural spaces to assess how resilient the building circulation flow is to fire.

The building consists of 22 floors; each floor has a circulation space. The circulation spaces connect the spaces together in each floor as well as connecting the floors to each other through the stairs and the elevators. Table 7.11 indicates the most significant circulation spaces in the building, those with a higher degree centrality. The results indicate that these are F1CIRCU with 76-degree centrality, F3CIRCU with 83-degree centrality, and F4CIRCU with 92-degree centrality, and F5CIRCU with 87-degree centrality, and F7CIRCU with 70-degree centrality. The degree centrality of a circulation space indicates the number of spaces with which it interacts. The network in Fig. 7.15 indicates the model of the circulation flow of the building's 22 floors and the spaces that are connected to the 22 circulation spaces, and the elevators and the stairs that link the circulation flow from one floor to another.

Table 7.11 Most significant circulation spaces in the building with a higher degree centrality

	Centrality measures		
Architectural space	**Degree centrality**	**Closeness centrality**	**Betweenness centrality**
F1CIRCU	76	19.2	11266
F3CIRCU	83	17.2	19003
F4CIRCU	92	16.2	23744
F5CIRCU	87	15.2	27364
F7CIRCU	70	13.2	28859

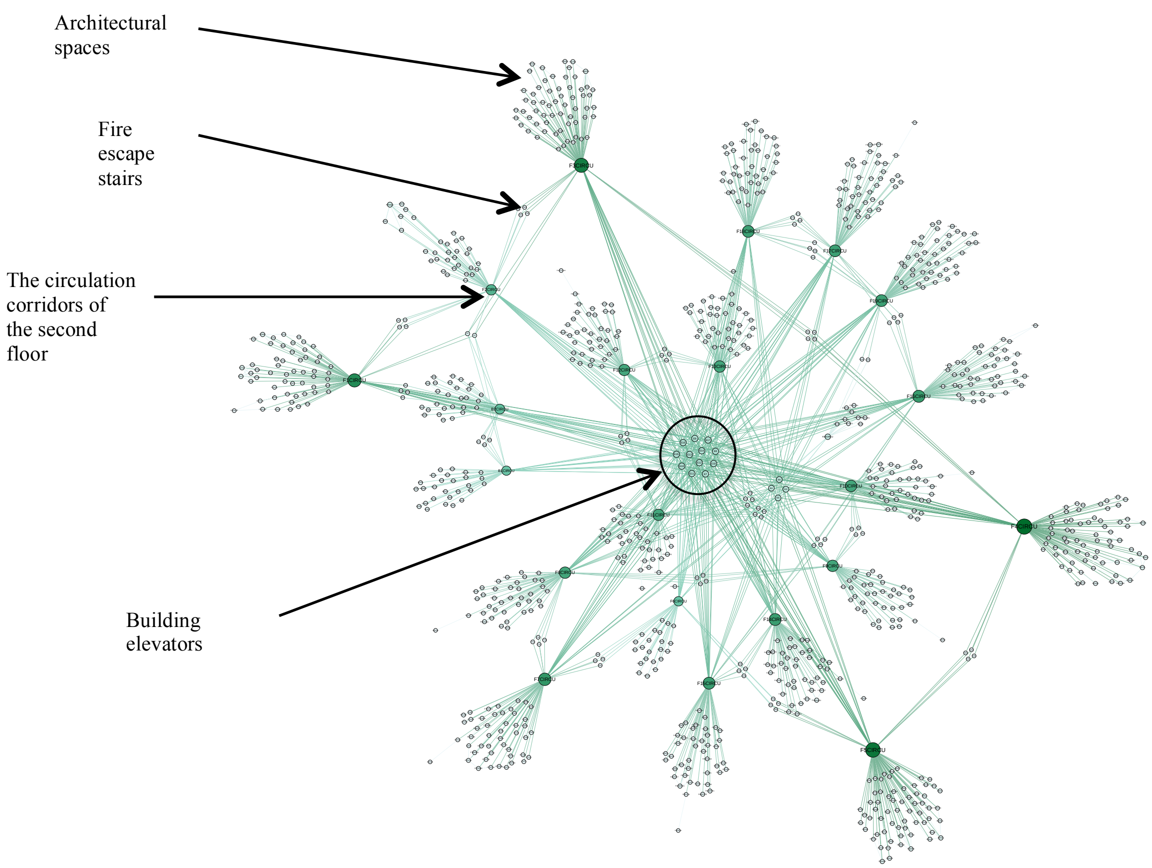

Fig. 7.19 Circulation flow of the building's 22 floors as well as the interaction between the architectural spaces

Moreover, this section of the research will identify how resilient the building's circulation is to any failure that happens in the circulation systems, such as fire. As shown in Fig. 7.19, each of the 22 circulation spaces is connected to 16 elevators. If there is a fire, the elevator nodes will fail to connect with the circulation flow, so this indicates changes in the typology of the building circulation network as well as changes in the network centrality measures and general characteristics. Fig. 7.20 indicates the typology of the circulation network if there is a fire. As shown, the elevator nodes have been removed, which demonstrates a significant change in the circulation flow and the dependence on the floors' stairs; there are four stairs per floor. In addition, Table 7.12 displays the results of the five significant circulation spaces after an elevator failure. In addition, Fig. 7.21 shows the changes in typology of the third floor circulation space if there is a fire. The right side of Fig. 7.21 shows that four stairs go to the fourth floor and four stairs go to the second floor; each of these stairs works as an alternative to the elevators in the case of fire or elevator failure. The left side of Fig. 7.21 indicates the network typology when removing the elevators, which shows a decrease in the number of nodes that link the circulation spaces, and thus a slowing of the circulation flow in the building. As a result, the increased number of fire stairs significantly enhances the efficiency of designing resilience in the building's circulation. The design of the circulation in this building indicates that the number of elevators is very high compared to the number of stairs.

Table 7.12 Significant circulation change of results when elevators of the building are removed from the network

	Centrality measures		
Architectural space	Degree centrality	Closeness centrality	Betweenness centrality
F1CIRCU	60	19.2	11218
F3CIRCU	67	17.2	18955
F4CIRCU	72	16.2	23680
F5CIRCU	67	15.2	27300
F7CIRCU	50	13.2	28795

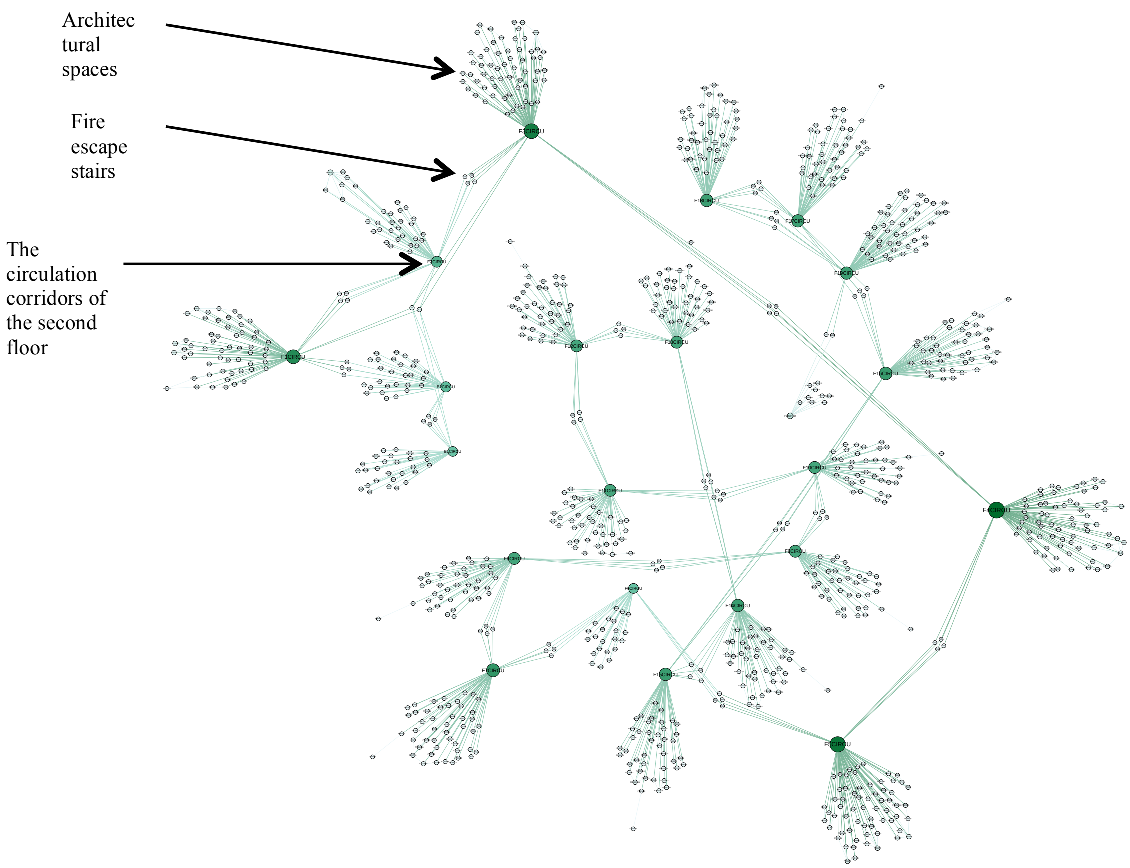

Fig. 7.20 Typology of the circulation flow network in the building in case of fire

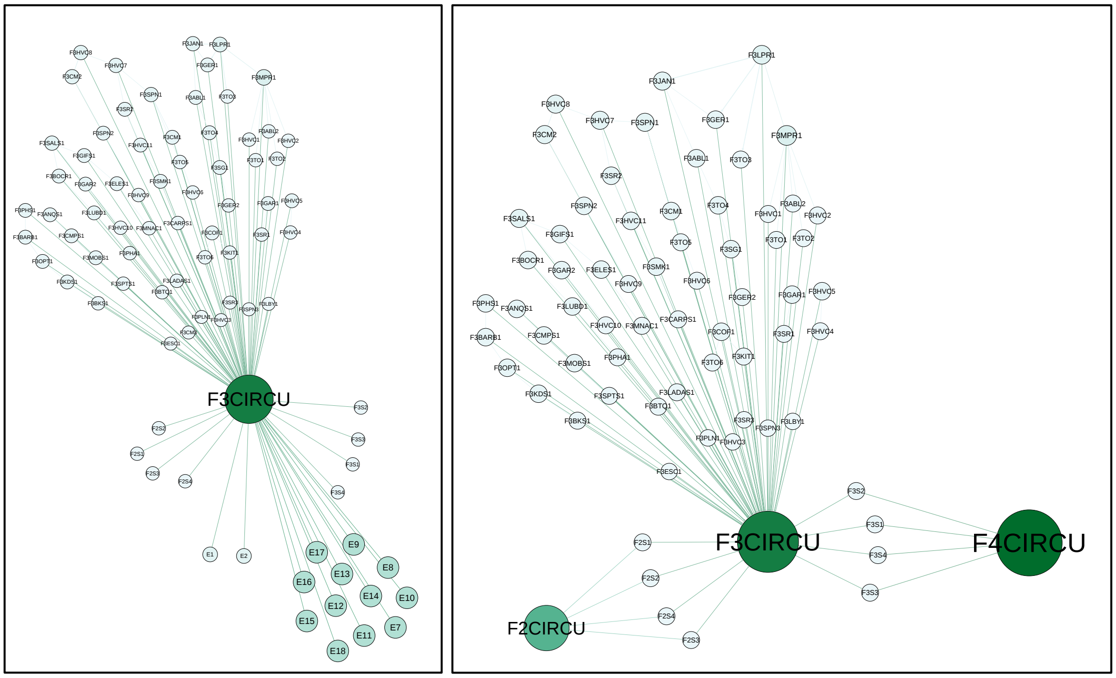

Fig. 7.21 Changes of the typology of the third floor circulation space in case of fire

Furthermore, this section of the research will assess the resilience of the floor plan to escape from fire if a fire happens in one of the architectural spaces as well as if a fire happens in any of the circulation corridors. Fig. 7.22 shows that there are eight corridors and four fire exits on the eighth floor, which are located in the concrete cores. Fig. 7.22 assumes that there is a fire in corridor F8CIRCU2, which is indicated by the symbol O, and another fire in corridor F8CIRCU1, indicated with the symbol A. The use of network analysis and modelling indicates the possibility of evacuating the users of the architectural spaces around the circulation spaces using the shortest circulation paths to go to the fire exits. Thus, in case of the two fires, O and A, there are two corridors that will fail to deliver the building users, which are F8CIRCU7 and F8CIRCU4, because the fires are located at the edges of these corridors. Users of the floor will need to use alternative ways to exit the floor. Fig. 7.23 shows the change of typology of the floor circulation flow when the two corridors with fire are removed. As an example, take two architectural spaces and determine their escape corridors, which are F8OFFC4 and F8OFFC6. The shortest path to escape from the fire using F8OFFC4 is through F8CIRCU1 and to F8S2, which is fire stairs number 2. And the shortest path to escape from the fire using F8OFFC6 is though F8CIRCU1 and to F8S3, which is fire stairs number 3. Therefore, the use of network analysis when designing the circulation floor of the building will significantly determine the fire escape route for building users in order to prevent a failure of the fire escape design floor plan. In addition, Fig. 7.24 indicates the overall connectivity between the circulation corridors and the fire escape stairs; the figure indicates that each of the corridors has an alternative corridor in case of fire to reach the fire stairs nodes. The use of this modelling will significantly enhance the assessment of the fire escape exits and stairs when designing building floor plans.

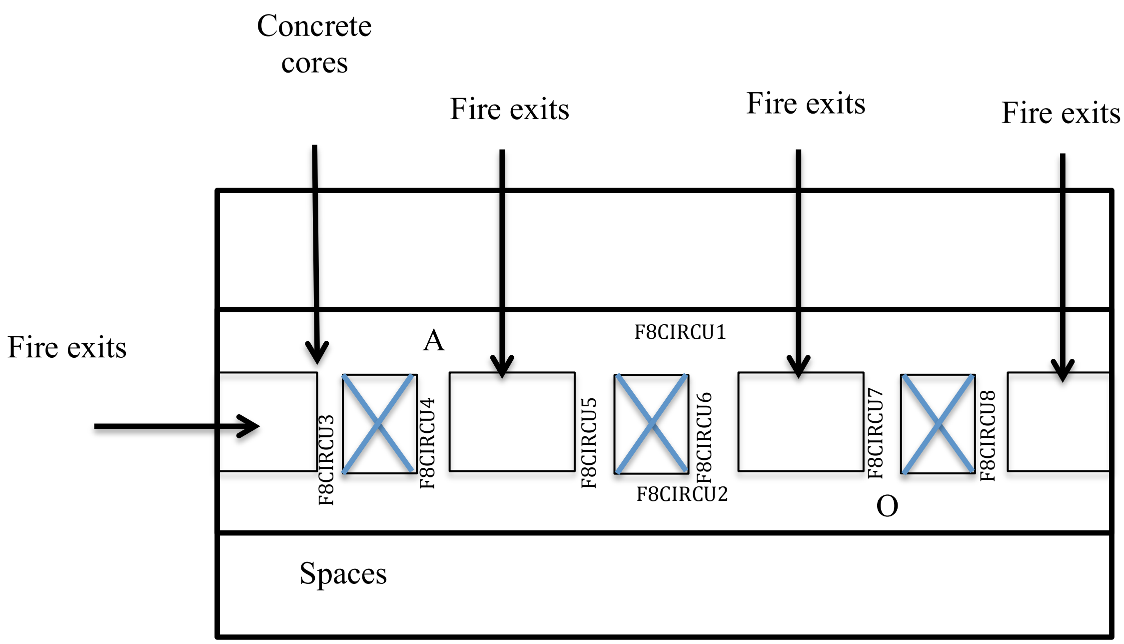

Fig. 7.22 Assumes that there is a fire in corridor F8CIRCU2, which is indicated by the symbol O, and another fire in corridor F8CIRCU1, indicated by the symbol A

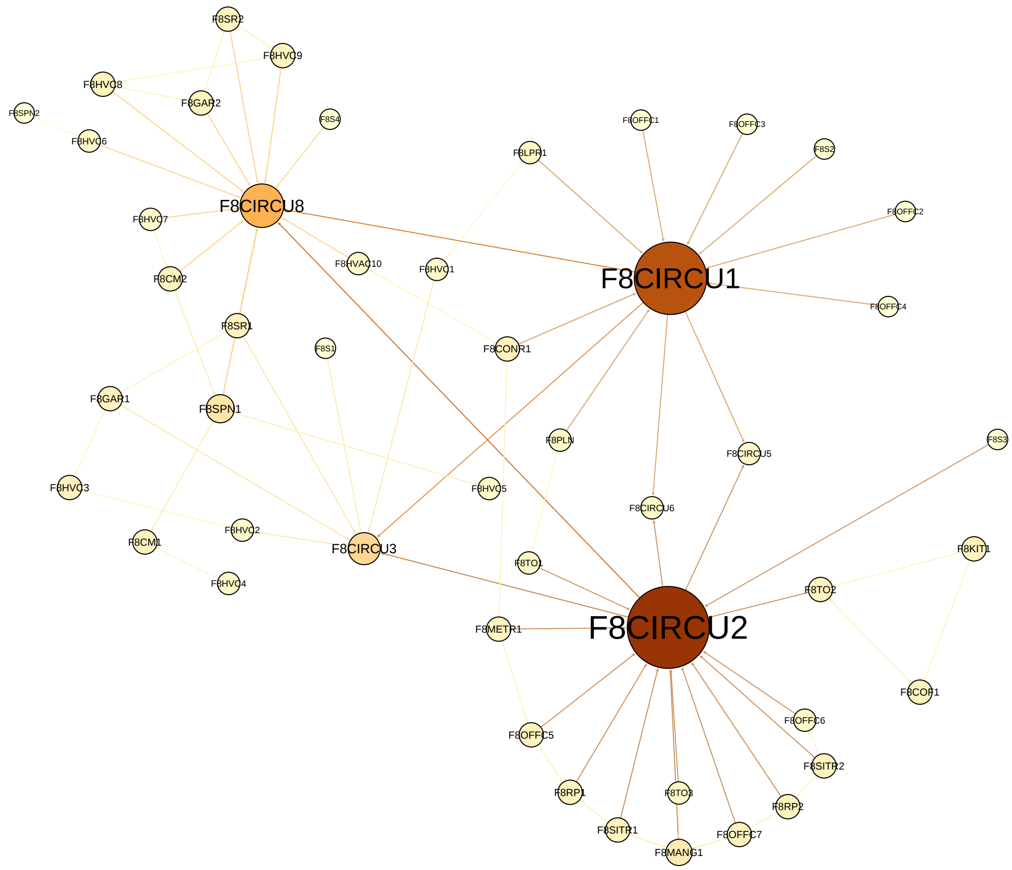

Fig. 7.23 Change of the typology of the floor circulation flow when the two corridors with fire are removed or blocked

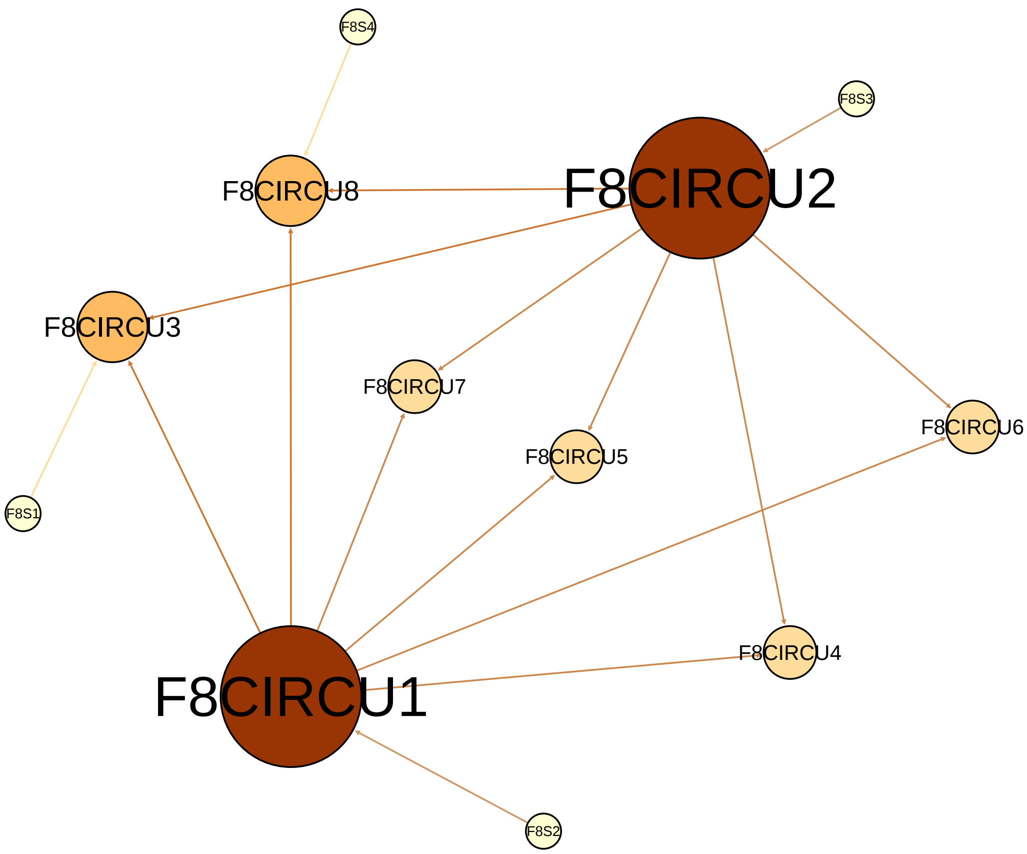

Fig. 7.24 Connectivity between the circulation corridors and the fire escape stairs of the eighth floor of the building

7.7.3 Assessment of the way finding in the building design layout using network modelling

According to Hölscher (2006), people face several problems when trying to find their way in buildings such as airports, hospitals and office buildings. This problem depends on their spatial cognition. Hölscher's (2006) research paper aims to link the design of the building to human spatial cognition using a survey of 12 people and their difficulties way finding in complex building design. In addition, the research represents a discussion of the seven spots that are most difficult to be found in a building and determines why building users find it so difficult to find their way to these spots. The study determined that the stairs are the most difficult aspect of the building in relation to difficulty in way finding in a building.

This section of the research will assess the difficulty of way finding for users using the network analysis technique and centrality measures by linking two floors of the building and finding the shortest paths that building users can use to reach their goal. Fig. 7.25 indicates the modelling of the circulation flow between the two floors of the building, which are the eighth and ninth floors. As shown in Figure 7.25, the circulation corridors of these two floors are linked through the building's elevators. In order for building users to travel from the eighth floor to the ninth floor they are required to go through one of the elevators using one of the main circulation corridors shown in Fig. 7.25, which are F8CIRCU1 and F8CIRCU2, and to reach any of the ninth floor spaces they have to travel through one of the two main corridors on the ninth floor, which are F9CIRCU1 and F9CIRCU2. For example, if a building user is trying to find her or his way from F8KIT1, which is the kitchen on the eighth floor, to F9OFFC3, the shortest path is from F8CIRCU7 to F8CIRCU1 and take the elevator from there to F9CIRCU1, which goes to F9OFFC3. This route uses three corridors, two of which are the main corridors that take users to the main vertical circulation of the building. The use of network analysis will significantly enhance the floor plans circulation design because it helps to identify and quantify the number of steps a building user is required to take to travel from one space to another. In addition, as the number of steps, which are the nodes of the shortest path, increase, this increases the way finding complexity for the building user. This assessment method of way finding can significantly enhance the floor plan design and indicate another design solution for the building's circulation flow.

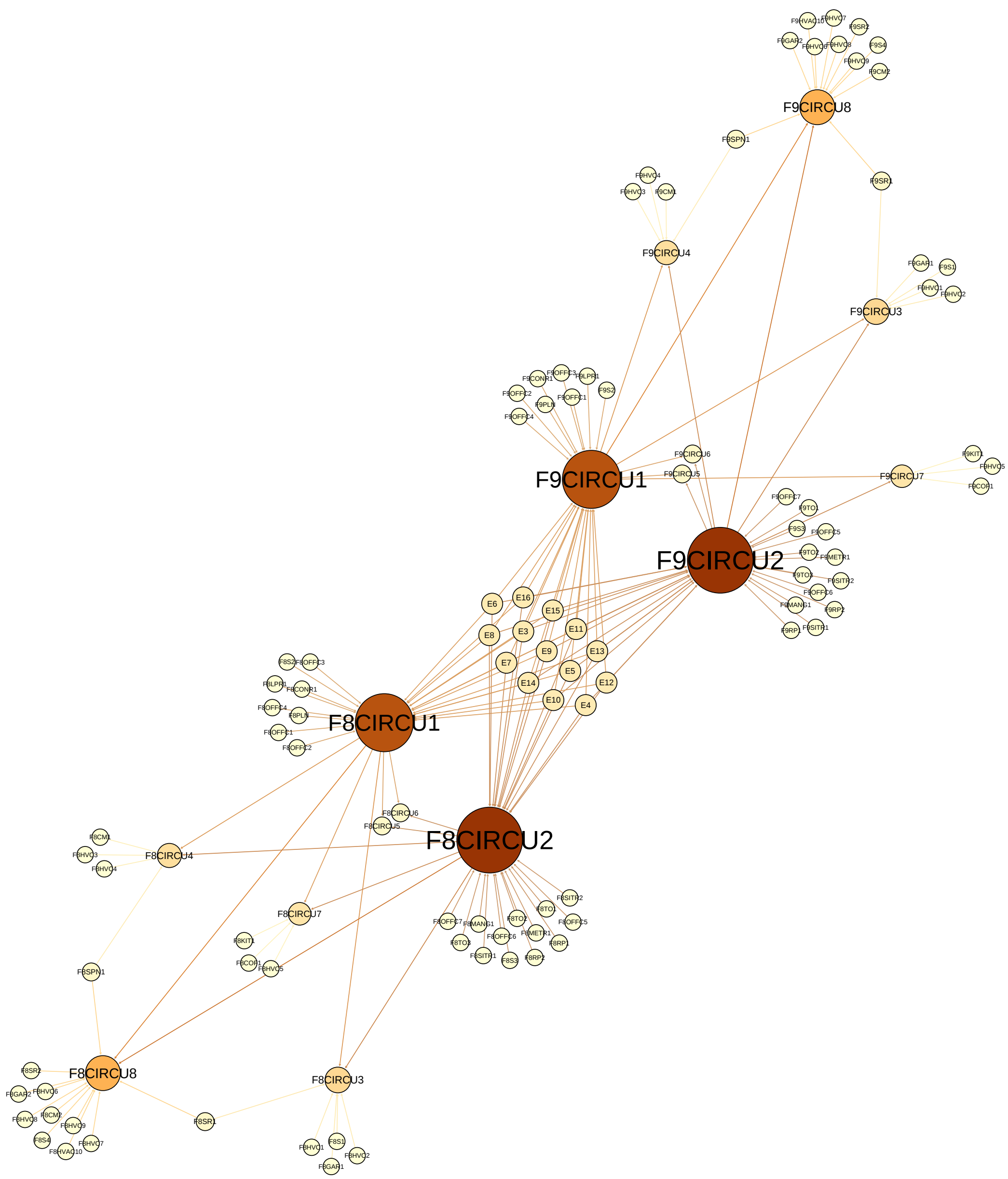

Fig. 7.25 Modelling of the circulation flow between two floors of the building, which are the eighth floor and the ninth floor

7.8 Conclusion

This chapter of the research has uncovered the very significant aspects of building architectural design complexity, which are the complexity of circulation flow between spaces, the functional relationship between spaces and the assessment of fire escapes in building layout design. The chapter started with a descriptive analysis of the building case study indicating the architectural design of the building and uncovering the typological characteristics of the building's circulation flow and assessing the building's resilient design. The chapter has provided an explanation of the floor plan for the building floors and the flow of the vertical circulation and floor circulation in the form of diagrams. In addition, the chapter has modelled the typology of the building's circulation flow as well as the interactions between the building's architectural spaces in the form of networks that are characterised by typological findings. The chapter has also presented an assessment of the building's floor plan in terms of its resilience to changes in the typology due to fire. In addition, the use of centrality measures has indicated the importance of the architectural spaces in terms of their connectivity as well as their importance in terms of escape from fire.

CHAPTER 8: THE TYPOLOGICAL CHARACTERISTICS AND ASSESSMENT OF RESILIENCE IN THE BUILDING'S STRUCTURAL SYSTEM DESIGN

8.1 Introduction

Designing a building's structural system requires several decisions that have to deal with a large number of components of systems that are connected together to form the building's structure. This chapter of the research will uncover one of the significant aspects that increases the complexity of designing a building, which is the design of a building structure, using King Faisal Specialist Hospital & Research Centre building in Riyadh, Saudi Arabia, as a case study to model the interactions between the building's structural components applying the methods used in the theoretical framework outlined in Chapter 4. In addition, the complexity of interactions between these structural components forms a complexity of systems, which needs to be assessed in terms of its resilience to certain design phenomena. Studying and modelling the interactions between the building's structural system components can be looked at from a complexity science point of view in order to enhance the efficiency of the structural system's performance. The main goal of this chapter is to model the complex interactions between the buildings structural system components using a new modelling approach, which is the network modelling technique. This modelling will result in models of connectivity between the building's structural system components that can be analysed and studied in terms of the resilience of the building's structural system. Moreover, this chapter will analyse the complexity of the building structural system's design in three main approaches, which are the descriptive analysis of the building's structural system, the uncovering of the typological characteristic of the building's structural system's networks, and the analysis and assessment of the important aspects of the building's structural system in terms of its resilience to design phenomena.

8.2 Descriptive analysis of the building's structural system design

The structural system of the building is a concrete structure, which consists of concrete columns and concrete floor slabs. The concrete columns are linked to the concrete foundation of the building, which transfers the building load to the ground. A four axis of concrete columns and one central axis of concrete core and the floor slabs are connected to these columns and concrete cores carry the floor of the building. Fig. 8.1 indicates the structural system design of the case study building. This research is modelling the interactions between the structural system components, which indicate the connectivity between the system components, and the flow and propagation of the effects on the building's structural system.

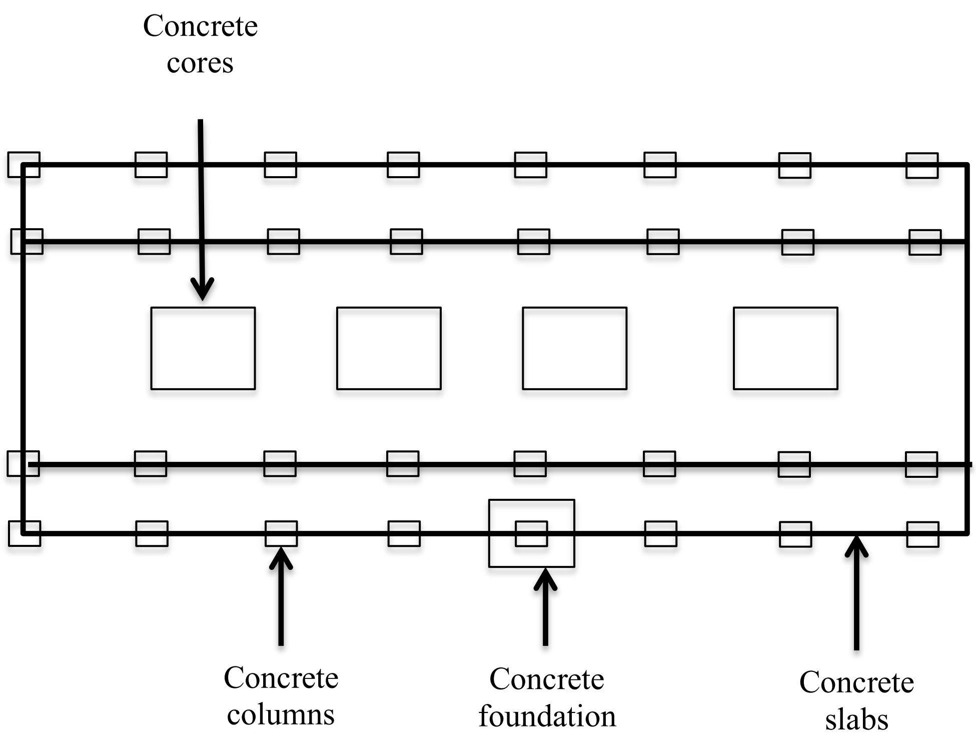

Fig. 8.1 Structural system design of the case study building

8.3 The network of interactions between the structural system's components

The structural system is defined in this research as the network that connects the structural components to each other, which is what structural engineers design as a building's structural layout. The components of the structural system are the floor slabs, the columns, the stairs, and the concert cores. The theoretical framework in Chapter 4 indicates the methods of modelling the interactions between the structural system components as a network. Each floor slab of the case study building is connected to a number of columns, concrete cores, and stairs. The columns are connected to the columns in the floors below and above, and the stairs are also connected to the concrete cores. Fig.

8.2 was modelled using Gephi and shows the typology of the interactions between the building's structural system components.

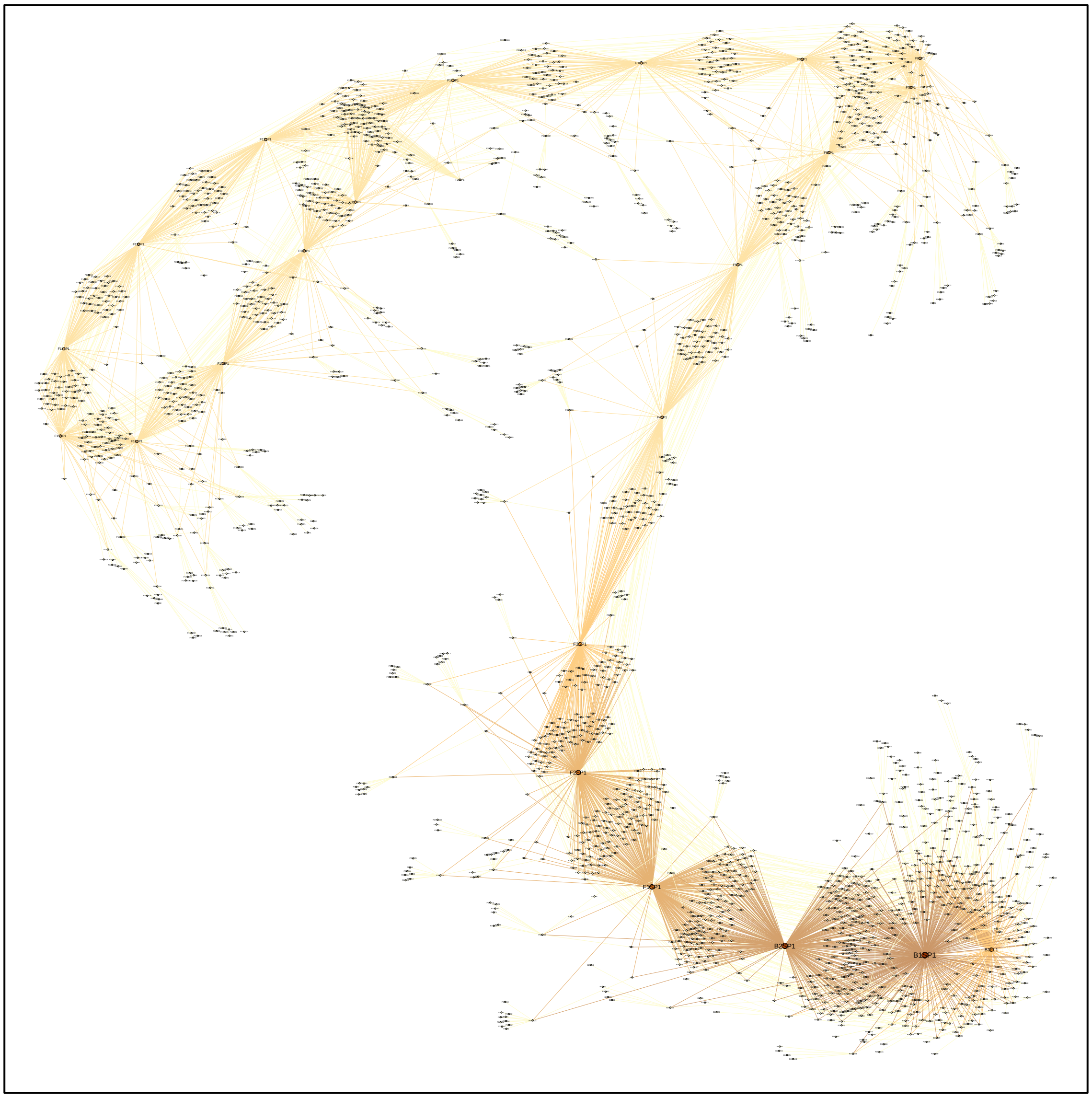

Fig.8.2 Typology of the interactions between the building's structural system components

The structural system network in Fig. 8.2, which was modelled using Gephi, consists of 2146 nodes and 4940 edges. The nodes represent the structural system components and the edges represent the interactions between the components. The structural network consists of 22 clusters; each cluster is around a floor slab. In addition, the density of interactions decreases as the floor slabs go up. Each cluster consists of a floor slab that is connected to the column of the floor above and the floor below and the concrete cores and the stairs, which are shown at the sides of the clusters. In addition, the larger the node the higher its degree centrality in the graph, so floor slabs are the largest nodes in the networks because they are connected to a large number of columns. For example, Fig. 8.3 shows the floor slab of the fourth floor, F4SP1, which is connected to the columns of the fourth and fifth floors; it also shows the concrete cores' interactions with the floor slabs and the stairs, and the interactions between the columns of the fourth and fifth floors. The F4SP1 degree centrality is 92, which indicates that the floor slab is connected to four stairs, four concrete cores and 84 concrete columns.

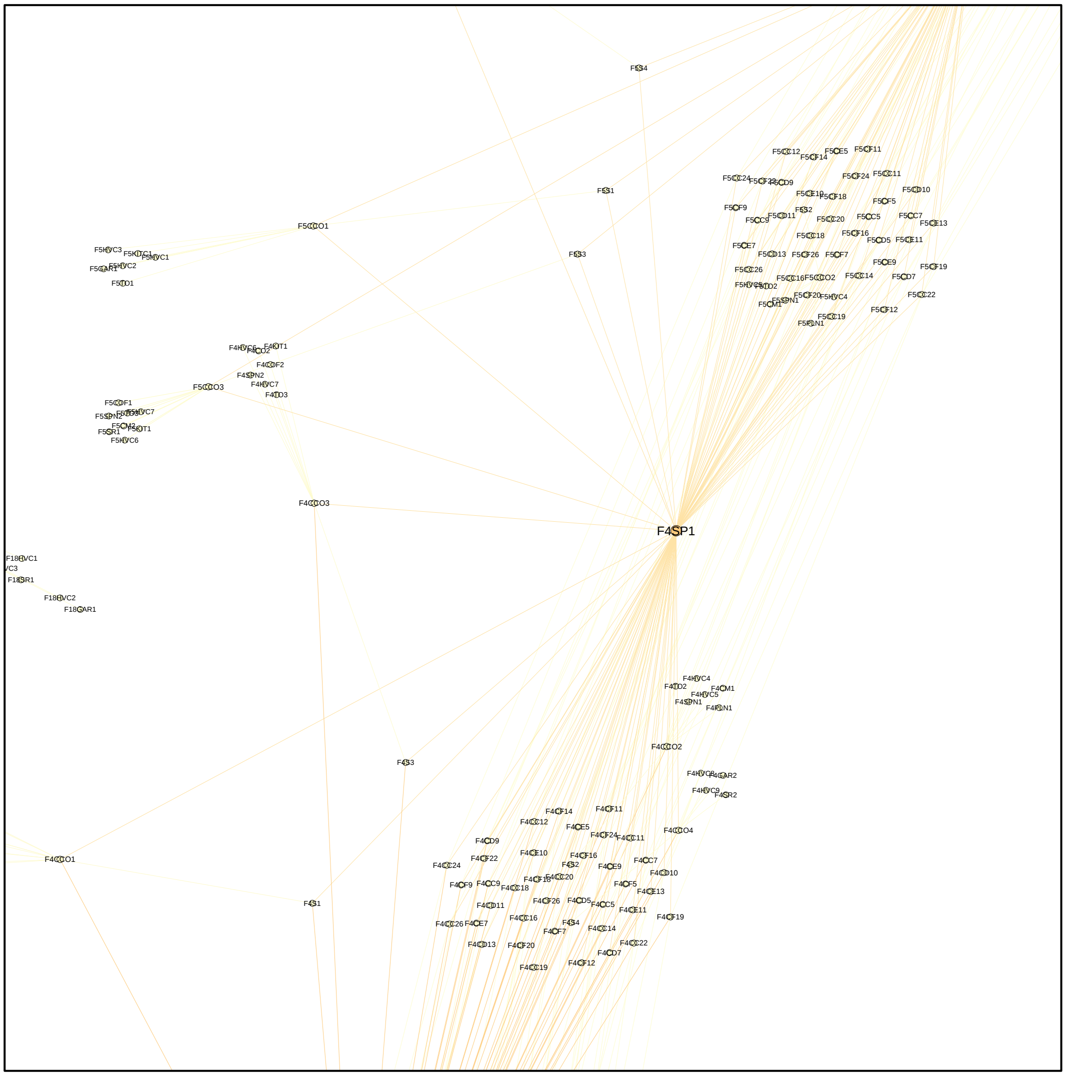

Fig. 8.3 Floor slab of the fourth floor, F4SP1, which is connected to the columns of the fourth and fifth floors

8.4 Network centrality measures of the building's structural system design

The centrality measures are very significant aspects of network analysis because they help to determine the significant components in terms of connectivity of the network, which are the most influential nodes in the network, in the building's structural system design. In this research, the centrality measures are used to enhance the ability to uncover the complex structural system design of the building and assess its resilience to certain phenomena. The centrality measures that are going to be calculated using Gephi in this research are the degree centrality, closeness centrality, and betweenness centrality. The following section indicates the definitions of the centrality measures that are going to be used in this research as well as the interpretation of these measures in the structural system design.

8.4.1 Degree centrality of building system components

This is defined as the number of edges that are connected to a node in a network. The measure of degree centrality indicates the number of edges that are connected to a node in the network. Table 8.1 shows the interpretation of the degree centrality measure for the building's structural system design network.

Table 8.1 Interpretation of the degree centrality measure for the building's structural system design network

The node in the network	The interpretation of the degree centrality in terms of connectivity in the building system's design
Structural system	The degree centrality of a structural system component such as the floor slabs, columns, concrete cores, and concrete walls indicates the number of components that are interacting with it. The degree centrality of a floor slab is the number of

	components that are connected to it. This number indicates the importance of the component in designing the building's structural system. As degree centrality of a structural component increases, it indicates that the component is in an important position in the building's structural system network.

8.4.2 Closeness centrality of building system components

The closeness centrality of a node measures its centrality in the system design network. Closeness centrality measures the average distance of a node to all nodes in the network and the more central the node in the network, the lower its distance to all other nodes in the network. Table 8.2 shows the interpretation of the closeness centrality measure for the building's structural system network.

Table 8.2 Interpretation of the closeness centrality measure for the building's structural system network

The node in the network	The interpretation of the closeness centrality in terms of connectivity in the building system's design
Structural system	The closeness centrality of a structural system component such as the floor slabs, columns, concrete cores, and concrete walls indicates the average distance of the component to all nodes in the network. It indicates how central the component is in the structural system network, which indicates its importance in terms of connectivity in the network.

8.4.3 Betweenness centrality of the structural system's design

Betweenness centrality measures the centrality of a node connecting other nodes in a network. It measures how often the node is positioned in shortest path between two nodes in the network. Betweenness centrality quantifies the number of times a node acts as a bridge to connect two nodes through the shortest path between them. This measurement indicates the importance of the nodes in the network in terms of passing the information through the network. The node with the highest value of betweenness centrality in a network is the most important node in the network flow. Table 8.3 indicates the interpretation of the betweenness centrality measure for the building's structural system network.

Table 8.3 Interpretation of the betweenness centrality measure for the building's structural system network

The node in the network	The interpretation of the betweenness centrality in terms of connectivity in the building system's design
Structural system	The betweenness centrality of a structural system component such as the floor slabs, columns, concrete cores, and concrete walls indicates the number of times the component works as a bridge to connect two components through the shortest path in the network. The betweenness centrality indicates the importance of the component in terms of connecting the components in the network.

8.5. General characteristic of centrality measures of the structural system design network

Table 8.4 indicates the general characteristics of the centrality measures of the nodes in the structural system network. The average degree centrality is 4.60, which is the average for the interactions between the nodes of the structural system. The closeness centrality average is 3.40; this indicates that the structural system network has very stronger connectivity because the average path that connects the nodes is very low. The average betweenness centrality of the nodes in the network is 345.19, which indicates the average of the nodes in the network working as a bridge to connect two nodes in the network. In addition, the highest degree centrality node in the structural network is B1SP1, which is the first basement floor slab, with a degree centrality of 357. When compared to the average degree centrality, which is 4.6, it indicates that the structural system interactions depend on a very large number of nodes that connect the system components together, which are the floor slabs. The highest closeness centrality of the structural network is 11.5, which is the result for a concrete wall in the basement. However, the highest betweenness centrality in the network is 12203.5, which is the first basement floor slab. The maximum interactions are in the basement floor because it is the most important space in terms of holding up the building's skeleton. The standard deviation of the degree centrality is 15.86, the closeness centrality is3.48, and the betweenness centrality 701. This indicates the variety in the results between the maximum interacting components and the standard deviation results, where there are a large number of components with a low number of interactions. The sum results indicate that the possibility of degree centrality in this network is very large due to the large number of components; the sum result for the degree centrality is 9880.

Table 8.4 General characteristics of the centrality measures of the nodes in the structural system network

	Centrality measures		
	Degree centrality	**Closeness centrality**	**Betweenness centrality**
MEANS	**4.60**	**3.40**	**345.19**
SD	**15.86**	**3.48**	**701.93**
SUM	**9880**	**7315.81**	**740794**
VAR	**251.58**	**12.17**	**492701.2**
MIN	**1**	**0**	**0**
MAX	**357**	**11.5**	**12203.5**

8.5.1 Centrality measures of the structural system's significant components

This section of the research will present the centrality measures of the structural system network, which was calculated using Gephi. The centrality measures applied are the degree centrality, closeness centrality and betweenness centrality. The nodes that will be investigated are the floor slabs of the building, because they are the most important nodes that link the network components together with higher degree centrality in the network. Table 8.5 indicates the centrality measures for the building's floor slabs.

The degree centrality of the floor slabs of the structural system represents the number of components that are interacting with a floor slab, which are floor columns, concrete cores and concrete walls. The results indicate that the floor slab with the highest degree centrality is B1SP1, which is the first basement floor slabs, with degree centrality of 357, and the floor slab with the lowest degree centrality is the twentieth floor slab with degree centrality of 42. The degree centrality measures the number of structural components that are connected to the floor slab and the table shows that the number of structural components that are interacting with the floor slabs decreases as the floors go up.

The closeness centrality of the floor slabs indicates the nodes that are most central in the network. The results indicate that the closeness centrality value decreases as the floors go up and increases as the floors gets closer to the basement floors.

The results of betweenness centrality indicate the number of times that the floor slabs work as a bridge to connect two nodes in the network through the shortest path. The results indicate that there is a pattern between the degree centrality of the floor slabs and the betweenness centrality of the node: as the number of degrees increase, the number of betweenness increases. The graph indicates the relations between the two measures of degree and betweenness centrality of the floor slabs.

Table 8.5 Centrality measures of the building's floor slabs

	Centrality measures		
Floor slabs	**Degree centrality**	**Closeness centrality**	**Betweenness centrality**
B1FL1	178	8.40	680
B1SP1	357	7.37	12203.5
B2SP1	324	7.34	11943
F1SP1	266	7.54	10161
F2SP1	240	7.7	8811
F3SP1	166	7.82	7353.5
F4SP1	92	8.05	5472
F5SP1	92	7.56	5168
F6SP1	92	7.07	4864
F7SP1	92	6.57	4560
F8SP1	92	6.08	4256
F9SP1	92	5.58	3952
F10SP1	92	5.09	3648
F11SP1	92	4.6	3344
F12SP1	92	4.11	3040
F13SP1	92	3.62	2736
F14SP1	92	3.14	2432
F15SP1	92	2.66	2128
F16SP1	92	2.2	1824
F17SP1	92	1.75	1520
F18SP1	92	1.33	1216
F19SP1	88	1	684
F20SP1	42	1	76

8.6. Assessment of structural design resilience

This section of the research will investigate the resilience of the building's structural design in terms of a very significant factor that has to be taken into consideration when designing a building's structural system, and which increases the complexity of the building's structural system design, which is the difficulty of determining the effect of an earthquake on specific components of the structural system as well as the propagation of the effect to the other structural components. The most significant component of a building's structural system in terms of resilience to earthquakes is the design of its foundations. This section of the research highlights the effects of an earthquake on the foundations as well as the components that are connected to the foundations. Table 8.6 displays the results for the most central foundations of the building's structural system. These foundations are the most propagated nodes in the structural system because they are connected to a very significant column that continues from the basements to the highest floors. Thus, a failure to one of these foundations because of an earthquake will affect a large number of components. This research uses network modelling to discover the components that are going to be affected when a one of the foundations fails due to an earthquake. Fig. 8.4 gives an example of the propagation of the failure of FOUN24, which is foundation number 24 in the building. As shown in Fig. 8.4, the propagation of the failure of FOUN24 affects B1CB4, which is the column that is connected to the foundation. In case of failure of B1CB4, the effect will propagate to several components, which are shown in graph number 2 in Fig. 8.4, and when the failure of these components is propagated, this indicates failure to a large number of components, which are shown in graph 3 in Fig. 8.4.

Table 8.6 Most central foundations of the building's structural system

Foundation of the building	Degree centrality	Closeness centrality
FOUN24	1	1.5
FOUN25	1	1.5
FOUN26	1	1.5

FOUN27	1	1.5
FOUN28	1	1.5
FOUN29	1	1.5
FOUN30	1	1.5

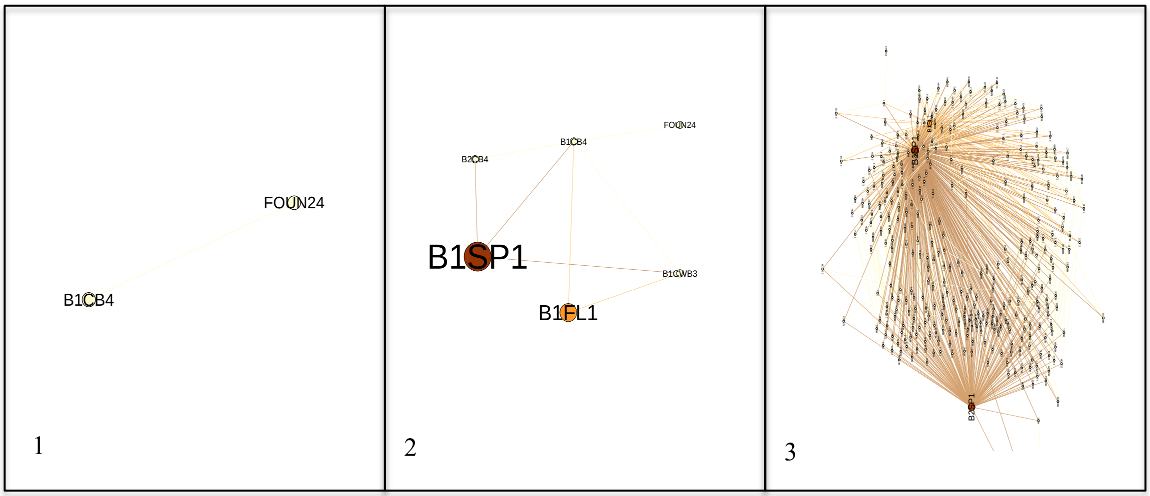

Fig. 8.4 An example of the propagation of the failure of FOUN24, which is foundation number 24 in the building

8.7 Conclusion

This chapter of the research has uncovered the very significant aspects of building structural design complexity, which are the complexity of designing a resilient structural system and the assessment of the structure to changes in and disconnections of a component of the system. The chapter started with a descriptive analysis of the building case study indicating the structural design of the building and the uncovering of its typological characteristics and the assessment of the resilience of the structural system. The chapter has provided an explanation of the floor plan of the building's structural design in the form of diagrams. In addition, the chapter has modelled the typology of the structural system as well as the interactions between the structural system's components in the form of a network that is characterised by its typological findings. The chapter has also presented the assessment of the building's structural components in terms of their resilience to changes in the typology due to a disconnection of a component of the system. In addition, the use of centrality measures has indicated the importance of the structural components in terms of their connectivity.

CHAPTER 9: THE TYPOLOGICAL CHARACTERISTICS AND ASSESSMENT OF RESILIENCE IN BUILDING SYSTEMS DESIGN

9.1. Introduction

Designing a building system requires several decisions that have to deal with a large number of components in the system that are connected together to form that system. This chapter of the research will uncover one of the significant aspects that increase the complexity of designing building systems, which is the design of a building as a product. It will use King Faisal Specialist Hospital & Research Centre building in Riyadh, Saudi Arabia, as a case study to model the interactions between the building system's components, applying the methods used in Chapter 4 on the theoretical framework. In addition, this complexity of interactions between these system components forms a complexity of systems, which needs to be assessed in terms of its resilience to certain design phenomena. Studying and modelling the interactions between the building system's components can be looked at from a complexity science point of view in order to enhance the efficiency of the building system's performance. The main goal of this chapter is to model the complex interactions between the building system's components using a new modelling approach, which are networks modelling techniques. This modelling will result in a model of connectivity between the building systems' components that can be analysed and studied in terms of the resilience of the building systems. Moreover, this chapter will analyse the complexity of the building systems design in three main approaches, which are the descriptive analysis of the building systems, the uncovering of the typological characteristics of the building systems' networks, and the analysis and the assessment of the important aspects of the building systems in terms of their resilience to design phenomena.

9.2. Descriptive analysis of the building systems design of the case studies

This section of the research describes the four building systems designs based on the case study building, King Faisal Specialist Hospital & Research Centre building in Riyadh, Saudi Arabia. The four systems are the envelope system design, the HVAC system design, the power system design, and the lighting system design. These building systems consist of several components, which interact with each other to perform the function for which each is designed. The interactions of each of the building systems' components are explained in the theoretical framework in Chapter 4. This descriptive analysis of the building case study's systems will provide examples the design of each of the building's four systems and indicate the function of each system and the function of its components.

9.2.1 Building envelope system design

The building envelope consists of curtain walls that are designed to allow light to access the spaces that are located in the elevation view. The connectivity of the envelope system is based on the curtain walls' connectivity to the structure of the building; the curtain walls are connected to the floor slabs and the columns of the elevation. The curtain walls consist of glass panels that rise from the floor to the ceiling of the architectural spaces. This research is modelling the connectivity of the windows of the curtain walls to the architectural spaces that are located in the elevation. The components of the envelope system are based on the theoretical framework of Chapter 4; they are the windows, which are connected to each other, and the architectural spaces that are connected to the windows. These interactions will indicate several outdoor effects on and advantages of the architectural spaces to the windows.

9.2.2 Building HVAC system design

The HVAC system of a building is its heating and ventilation air-conditioning. This system maintains a comfortable temperature in the building's architectural spaces. The building's HVAC system consists of air-conditioning machines, which are located on the services floor, which is the sixth floor of the building. These machines are connected to the HVAC rooms, which are located in the concrete cores of the building through air supply and return ducts. These ducts are designed in a grid that supplies and returns air to the building's architectural spaces. This research models the components in the HVAC system's connectivity, which are the connectivity of the air-conditioning machines to the HVAC rooms and the connectivity of the ducts to the architectural spaces. This modelling will significantly demonstrate the effects of any of the system components' failure to function.

9.2.3 Building power system design

The building's power system provides the building with electricity. The system consists of a generator that generates electricity to the whole building. The generator is located on the first floor of the building and provides electricity to the main panels rooms, which are located in the building's concrete core. There is a main panels room in the same location on each floor of the building, and each is connected with wires that provide the power lines for each floor, which provides the architectural spaces with electricity. This research will model the interactions of these components in order to determine the flow of electricity in the building as well as to indicate the effect that failure of one of the system's components will have on the system.

9.2.4 Building lighting system design

The lighting system of the building is another power grid that is connected to the generator and its components, which are the lighting lines and the lighting fixtures, are connected to the main panels room on the floor to get electricity. The modelling of this system's interactions will demonstrate the effect of failure of any of these components.

9.3. Modelling and uncovering the typological characteristic of the building system design

This section of the research will model the interactions of the building system components in the form of networks; each network will present a building system based on a building case study. The networks will include the interactions between each system component of the building system design. Each of the building components will be presented as a node in the network and each of the links or the connections between the components will be presented as an edge in the network models. The goal of modelling the interactions of the building system components is to investigate and assess the building system's resilience to certain design phenomena. Thus, the investigation and the assessment will be established by modelling the building system networks using the social network analysis software program Gephi, to uncover the typology of the building system design. Then the social network analysis measures will be applied to the network to identify the significance of the components in terms of their effect on the system and the system's resilience.

9.3.1 Building system interaction network typologies

In this section of the research, the networks of interactions of the building system design will be presented based in the interactions of the theoretical framework in Chapter 4. This interaction is based on the connectivity of each building system's design. The envelope system will be modelled based on the interactions of the components with the architectural spaces, the HVAC system will be modelled based on the interactions of the components with the architectural space, and the power and the lighting systems will be modelled based on the interactions with the architectural spaces.

9.3.1.1 The network of interactions for the envelope system components

The envelope system is defined in this research as the network that connects the architectural spaces to the envelope system components, which is what the structural and the architectural engineers design as the elevation of the building. The components of the envelope system are the windows, and the architectural spaces that are connected to them. The theoretical framework in Chapter 4 indicates the methods of modelling the interactions of the envelope system components as a network. Each window of the building is connected to a space or a number of spaces. Fig. 9.1, which was modelled using Gephi, shows the typology of the interactions of the building's envelope system components.

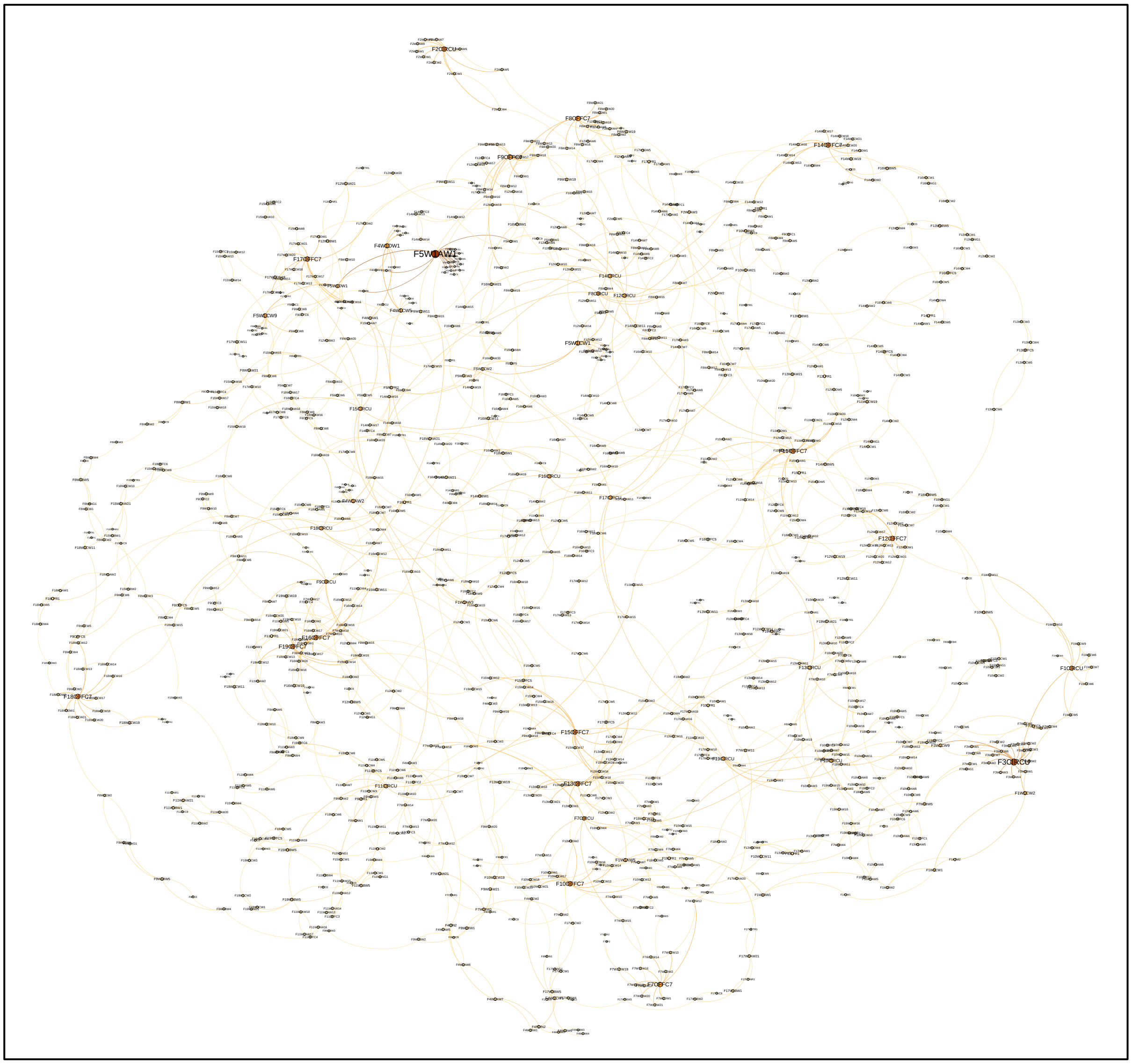

Fig. 9.1 Typology of the interactions of the building envelope system components

The envelope system network in Fig. 9.1, which was modelled, using Gephi, consists of 1088 nodes and 1626 edges. The nodes represent the envelope system components and the edges represent the interactions between the components. The network nodes are the architectural spaces and the windows that are connected to the architectural spaces and the windows that are connected to the windows. In addition, the larger the node, the higher its degree centrality in the graph; the spaces that are larger indicate that they are connected to a large number of windows. For example, Fig. 9.2 shows office number 7 on the eighteenth floor, F18OFFC7, which has a 10-degree centrality; this indicates that the node is connected to 10 windows.

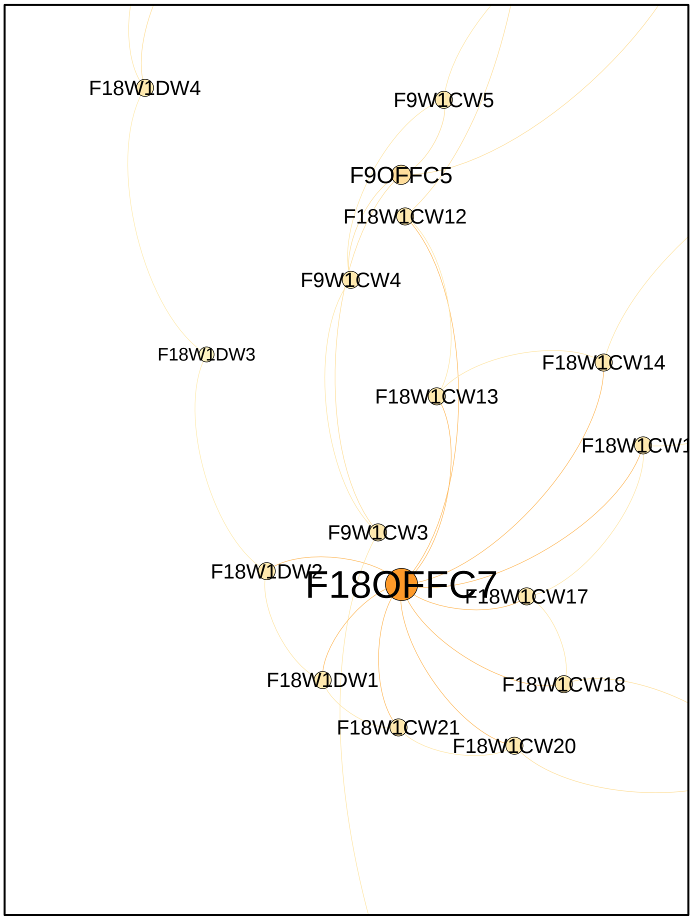

Fig. 9.2 Office number 7 on the eighteenth floor, F18OFFC7 and its connectivity to the envelope system's components

9.3.1.2 Network of interactions for the heating and ventilation air-conditioning system components

The HVAC system is defined in this research as the network that connects the HVAC system's components to the architectural spaces, which is what the mechanical engineer designs as the layout of the building's HVAC system. The theoretical framework in

Chapter 4 indicates the method used to model the HVAC system. The components of the HVAC system are the HVAC rooms, the supply ducts, and the return ducts. Fig. 9.3 indicates the methods of modelling the interactions of the HVAC system components as a network. Each HVAC room is connected to several supply ducts that are connected to architectural spaces, and the HVAC rooms are also connected to return ducts that are connected to the architectural spaces. Fig. 9.3, which was modelled using Gephi, shows the typology of the interactions of the building's HVAC system components.

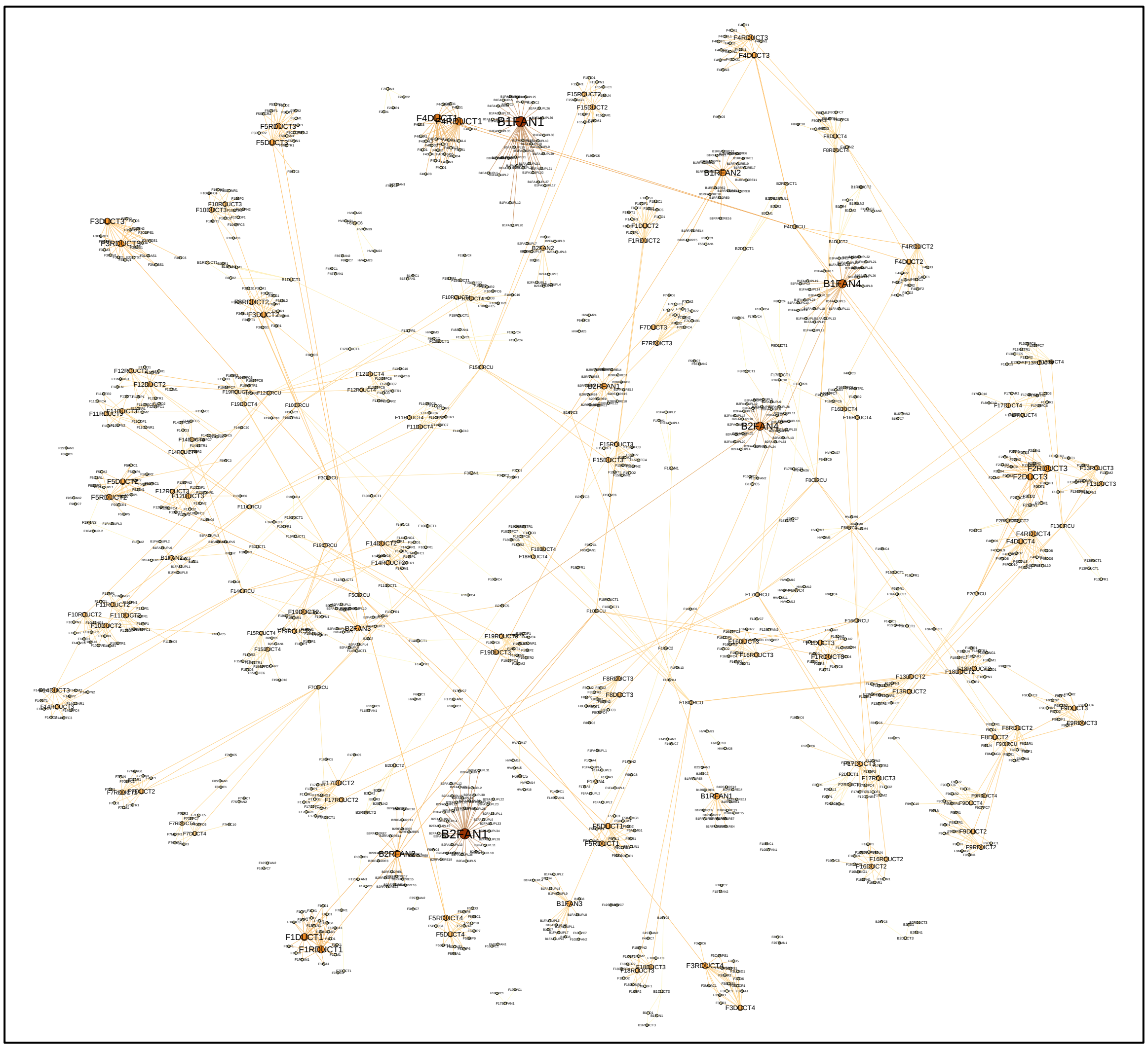

Fig. 9.3 Typology of the interactions for the building's HVAC system components

The HVAC system network in = Fig. 9.3, which was modelled using Gephi, consists of 1245 nodes and 1772 edges. The nodes represent the HVAC system components and the edges represent the interactions between the components. The network nodes are the ducts and the return ducts and the HVAC rooms that are connected to and the architectural spaces that are connected to the ducts. Moreover, the larger the node, the higher its degree centrality in the components of the HVAC system; those that are larger in the graph indicate a large number of interactions with other components of the system and the architectural spaces. For example, Fig. 9.4 indicates the cluster of two types of ducts that are connected to architectural spaces, which are F1DUCT1 and F1RDUCT1; both ducts are connected to the HVAC room, and they provide the architectural spaces with air and return to the HVAC system.

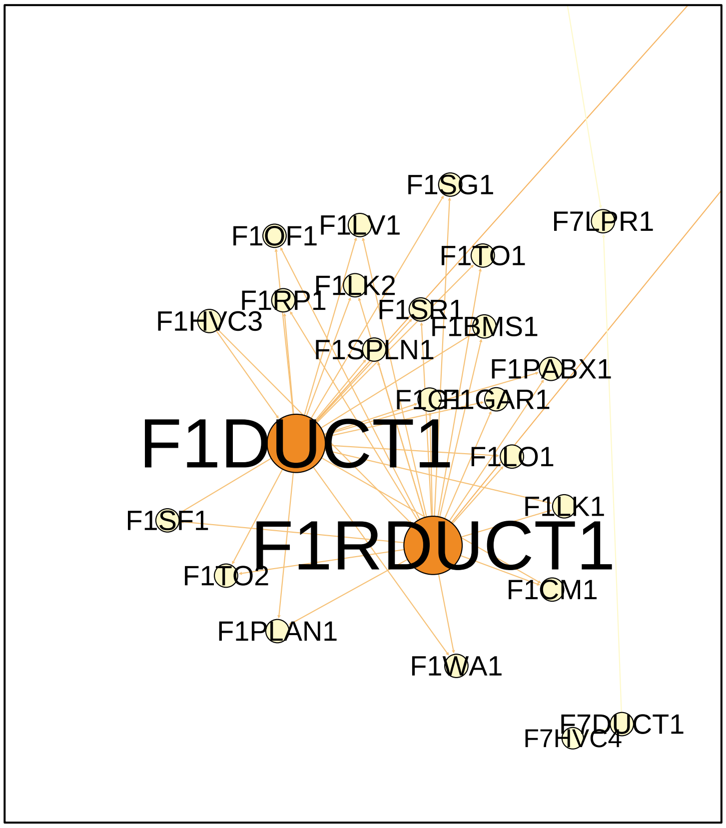

Fig. 9.4 Cluster of two types of ducts that are connected to architectural spaces, which are F1DUCT1 and F1RDUCT1

9.3.1.3 Network of interactions for the power system components

The power system is defined in this research as the network that connects the power system components to the architectural spaces, which is what the electrical engineer designs as the layout of the building's power system. The theoretical framework in Chapter 4 indicates the method used to model the power system. The components of the power system are the main panels room, which provides the electricity from the generator room, the power lines, which are connected to the main panels, and the receptacles. The power lines and the receptacles are connected to the architectural spaces. Fig. 9.5 shows the methods of modelling the interactions of the power system components as a network.

Each main panels room is connected to a number of power lines; those power lines are connected to several receptacles and both are located in the architectural spaces. Fig. 9.5 was modelled using Gephi, and indicates the typology of the interactions for the building's power system components.

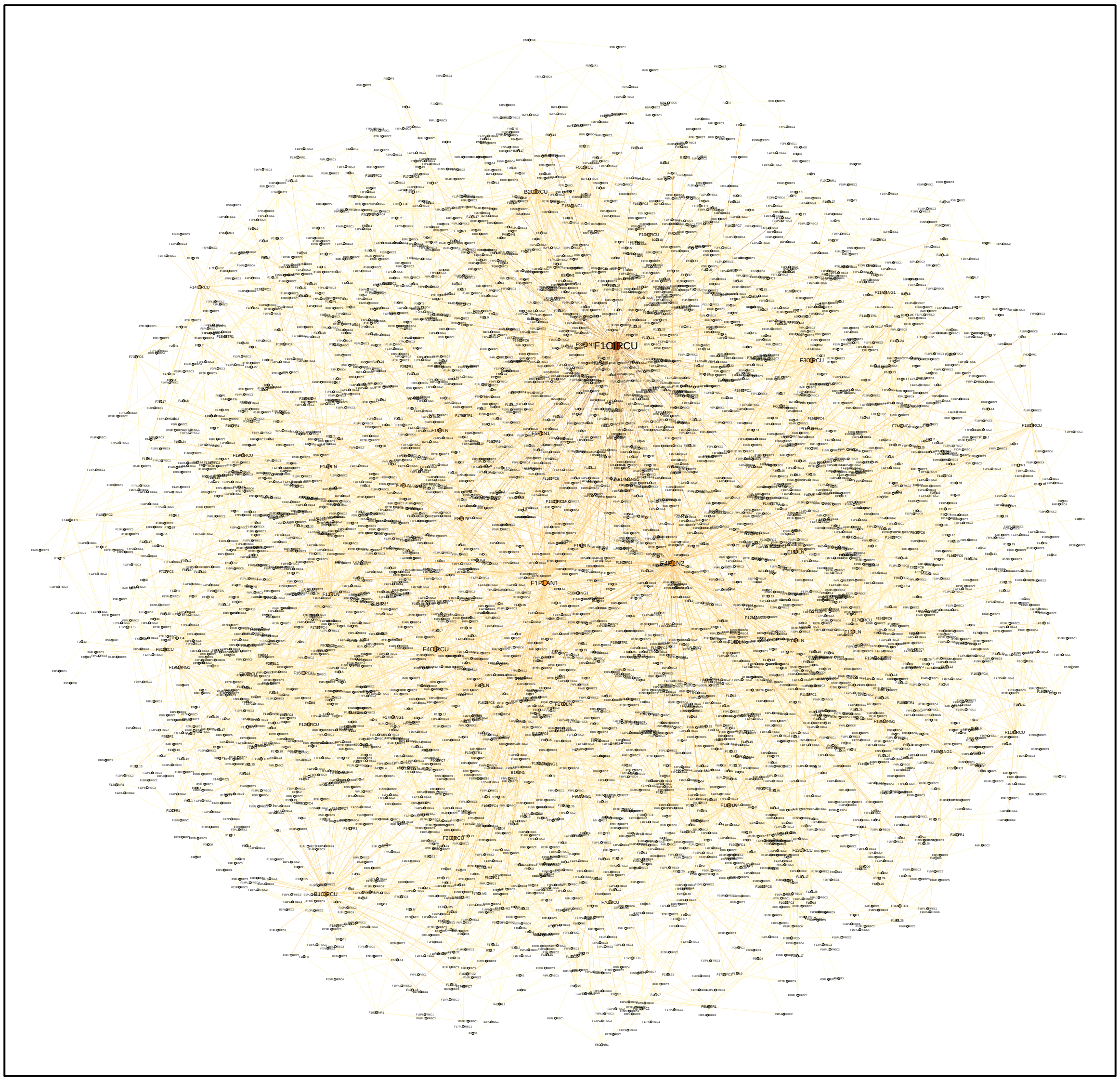

Fig. 9.5 Typology of interactions for the building's power system components

The power system network in the graph, which was modelled, using Gephi, consists of 4034 nodes and 7124 edges. The nodes represent the components of the power system and the edges represent the interactions between the components. The network nodes are the architectural spaces, main panels rooms, power lines, and receptacles. The larger the node, the more interacted it is, with a higher degree centrality. For example, Fig. 9.6 shows the density of interactions for the power system components with the F1CIRCU node, which is the first floor circulation space.

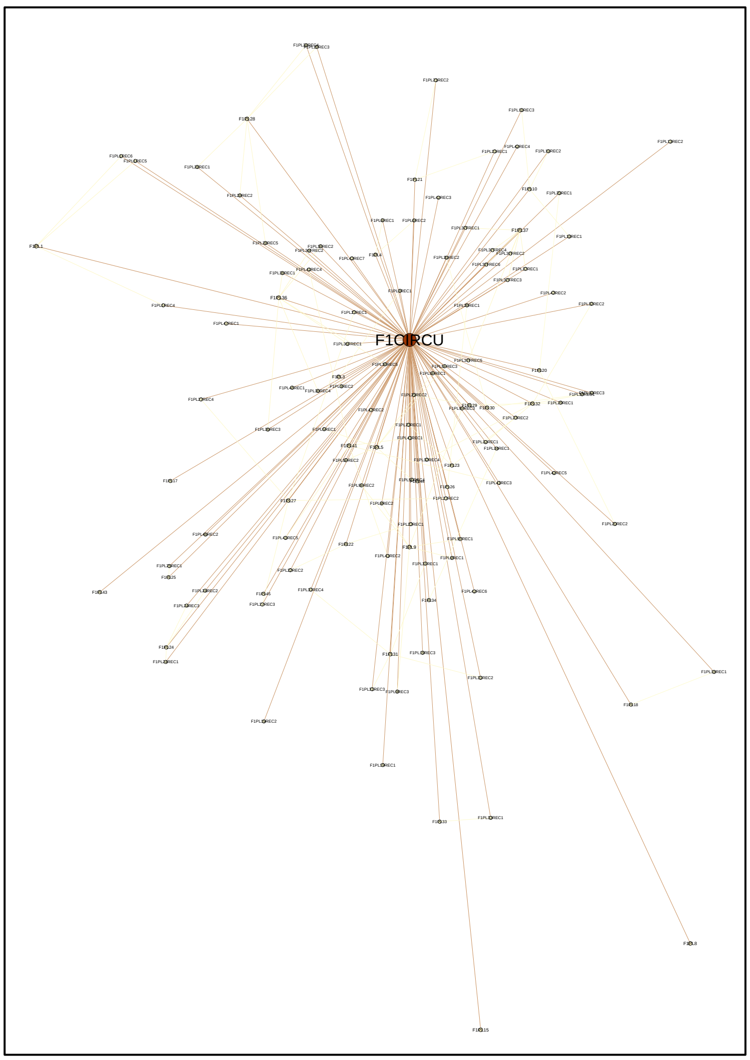

Fig. 9.6 Power system components' interactions with the F1CIRCU node, which is the first floor circulation space

9.3.1.4 Network of interactions for the lighting system components

The lighting system is defined in this research as the network that connects the lighting system components to the architectural spaces, which is what the electrical engineer designs as the layout of the building's lighting system. The components of the lighting system are the main panels room, which provides the electricity from the generator room, the lighting lines, which are connected to the main panels rooms, and the lighting fixtures. The lighting lines and lighting fixtures are connected to the architectural spaces. The theoretical framework in Chapter 4 indicates the methods of modelling the interactions of the lighting system components as a network. Each main panel room is connected to a number of lighting lines; those lighting lines are connected to several lighting fixtures, and both are located in the architectural spaces. Fig. 9.7 was modelled using Gephi and indicates the typology of the interactions for the building's lighting system components.

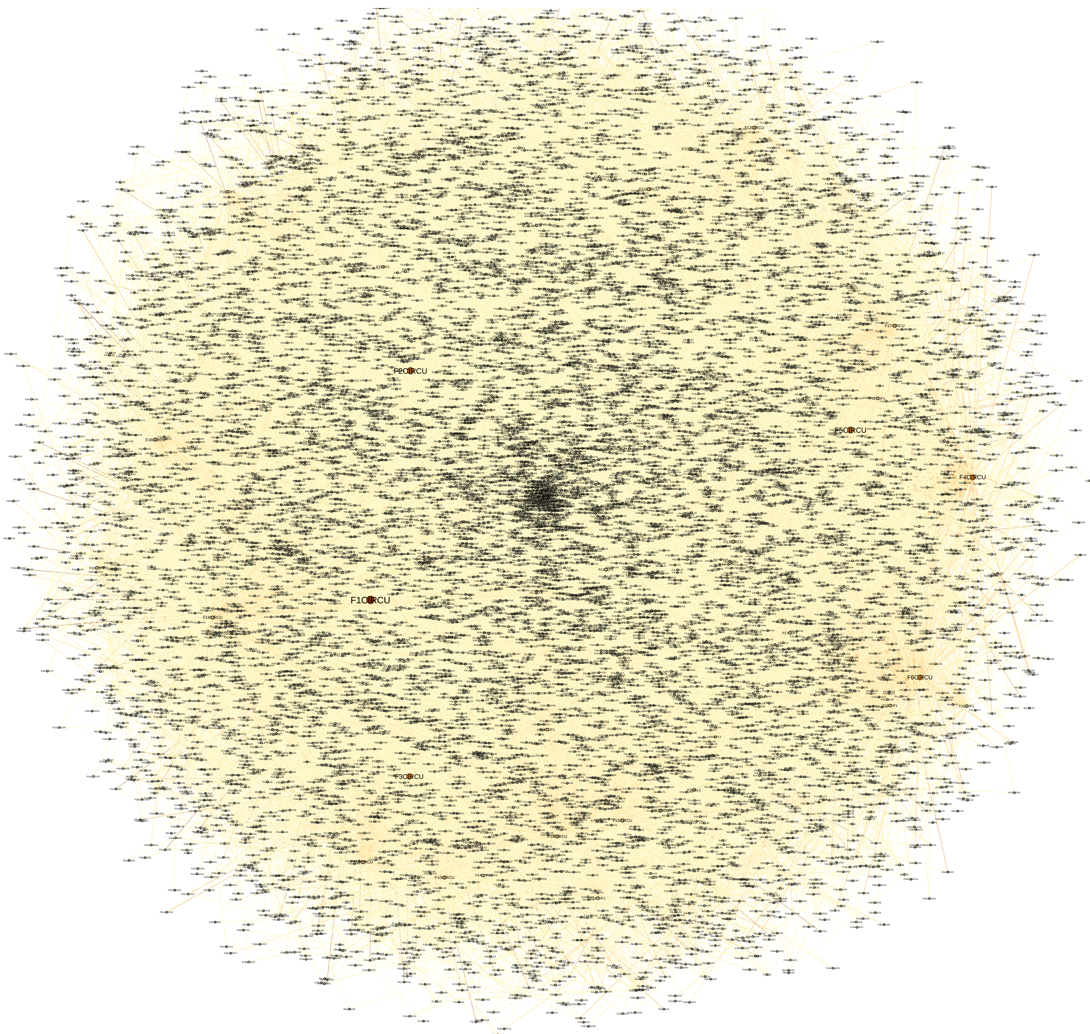

Fig. 9.7 Typology of the interactions for the building's lighting system components

The lighting system network in Fig. 9.7, which was modelled using Gephi, consists of 11199 nodes and 20551 edges. The nodes represent the components of the lighting system and the edges represent the interactions between the components. The network nodes are the architectural spaces, main panels rooms, lighting lines, and lighting fixtures. The larger the node, the more interacted it is, with a higher degree centrality.

9.4. Network centrality measures of the building system design

The centrality measures are very significant aspects in network analysis because they help to determine the significant components in terms of connectivity of the network, which are the most influential nodes in the network, of the building systems design. In this research, the centrality measures are used to enhance the ability to uncover the complex systems design of the building and assess the resilience of those systems to certain phenomena. The centrality measures that are going to be calculated using Gephi in this research are the degree centrality, closeness centrality, and betweenness centrality. The following section provides the definitions of the centrality measures that are going to be used in this research, as well as the interpretation of them.

9.4.1 Degree centrality of building system components

This is defined as the number of edges that are connected to a node in a network. The measure of degree centrality indicates the number of edges that are connected to a node in the network. Table 9.1 displays the interpretation of the degree centrality measure to the building system network.

Table 9.1 Interpretation of the degree centrality measure to the building system network

The node in the network	The interpretation of the degree centrality in terms of connectivity in building systems design
Envelope system	The degree centrality of the envelope system components such as windows and architectural spaces that are connected to the windows indicates the number of components that interact with each one. The degree centrality of a window is the number of architectural spaces and windows that are connected to it. This number indicates the importance of the component in designing the envelope system of the

	building. As the degree centrality of an envelope component increases, it indicates that the component is in an important position in the network of the building's envelope system design.
HVAC system	The degree centrality of the HVAC system components such as HVAC rooms, ducts, returns ducts, and architectural spaces indicates the number of components that interact with each one. The degree centrality of an HVAC room is the number of ducts and return ducts that are connected to it. This number indicates the importance of the component in designing the HVAC system of the building. As the degree centrality of a HVAC component increases, it indicates that the component is in an important position in the network of the building's HVAC system design.
Power system	The degree centrality of the power system components such as main panels rooms, power lines, and receptacles, and architectural spaces indicates the number of components that interact with each one. The degree centrality of a main panels room is the number of power lines that are connected to it. This number indicates the importance of the component in designing the power system of the building. As the degree centrality of a power system component increases, it indicates that the component is in an important position in the network of the building's power system design.
Lighting system	The degree centrality of the lighting system components such as main panels room, lighting lines, and lights, and architectural spaces indicates the number of components that interact with each one. The degree centrality of a main panels room is the number of lighting lines that are connected to it. This number indicates the importance of the component in designing the lighting system of the building. As the degree centrality of the lighting system component increases, it indicates that the component is in an important position in the network of the building's lighting system design.

9.4.2 Closeness centrality of building systems components

The closeness centrality of a node measures the centrality of the node in the system design network. Closeness centrality measures the average distance of a node to all nodes in the network and the more central the node in the network, the lower its distance to all other nodes in the network. Table 9.2 indicates the interpretation of the closeness centrality measure to the building system network.

Table 9.2 Interpretation of the closeness centrality measure to the building system network

The node in the network	The interpretation of the closeness centrality in terms of connectivity in building systems design
Envelope system	The closeness centrality of an envelope system component such as windows or architectural spaces that are connected to the windows indicates the average distance of the component to all nodes in the network. It indicates how central the component is in the envelope system network, which indicates its importance in terms of connectivity in the network.
HVAC system	The closeness centrality of an HVAC system component such as HVAC rooms, ducts, and returns ducts, and architectural spaces indicates the average distance of the component to all nodes in the network. It indicates how central the component is in the HVAC system network, which indicates its importance in terms of connectivity in the network.
Power system	The closeness centrality of a power system component such as main panels rooms, power lines, receptacles, and architectural spaces indicates the average distance of the component to all nodes in the network. It indicates how central the component is in the power system network, which indicates its importance in terms of connectivity in the network.

Lighting system	The closeness centrality of a lighting system component such as main panels rooms, lighting lines, lighting fixtures, and architectural spaces indicates the average distance of the component to all nodes in the network. It indicates how central the component is in the lighting system network, which indicates its importance in terms of connectivity in the network.

9.4.3 Betweenness centrality of building systems components

Betweenness centrality measures the centrality of a node in connecting other nodes in networks. It measures how often the node is positioned in the shortest path between two nodes in the network. Betweenness centrality quantifies the number of times a node acts as a bridge to connect two nodes through the shortest path between them. This measurement indicates the importance of the nodes in the network in terms of passing the information through the network. The node with the highest value of betweenness centrality in a network is the most important node in the network flow. Table 9.3 indicates the interpretation of the betweenness centrality measure in the building system network.

Table 9.3 Interpretation of the betweenness centrality measures in the building system network

The node in the network	The interpretation of the betweenness centrality in terms of connectivity in building systems design
Envelope system	The betweenness centrality of a structural system component such as windows and architectural spaces that are connected to the windows indicates the number of times the component works as a bridge to connect two components through the shortest path in the network. The betweenness centrality indicates the importance of

	the component in terms of connecting the components in the network.
HVAC system	The betweenness centrality of a structural system component such as HVAC rooms, ducts, return ducts, and architectural spaces indicates the number of times the component works as a bridge to connect two components through the shortest path in the network. The betweenness centrality indicates the importance of the component in terms of connecting the components in the network.
Power system	The betweenness centrality of a structural system component such as main panels room, power lines, receptacles, and architectural spaces indicates the number of times the component works as a bridge to connect two components through the shortest path in the network. The betweenness centrality indicates the importance of the component in terms of connecting the components in the network.
Lighting system	The betweenness centrality of a structural system component such as main panels room, lighting lines, and lighting fixtures, and architectural spaces indicates the number of times the component works as a bridge to connect two components through the shortest path in the network. The betweenness centrality indicates the importance of the component in terms of connecting the components in the network.

9.5. General characteristics of the envelope system design network

Table 9.4 indicates the general characteristics of the centrality measures of the nodes in the envelope system. The average degree centrality is 2.99, which are the average interactions between the nodes in the system. The closeness centrality is 16.52, which indicates that the connectivity between the nodes in the envelope system is not very strong, because the closeness average is very high compared to other systems in the building. The average betweenness centrality of the nodes in the envelope network is

1065.42, which is the average of the nodes working as a bridge to connect two nodes in the system. In addition, the node with the highest degree centrality in the envelope system is F5W1AW1, with 19, which is the window on the fifth floor, façade A. When compared to the average degree centrality of all nodes in the system, the gap is not as high as for the architectural and the structural system. The highest closeness centrality of the envelope system network is 26.77, for F7W1CW1. However, the highest betweenness centrality result in the envelope network was 1771, for the eighth floor, façade A, and window 20. In addition, the standard deviation of the degree centrality is 1.41, which indicates that there is only a small degree of variation between the results for the nodes in the network, the closeness centrality is 11.58, and the betweenness centrality is 793.81. The standard deviation result is close to the range of the nodes results, which shows that the interaction in the network does not depend on a large node that controls the system's connectivity. The sum result indicates the possibility of interactions of the degree centrality in this network, which is 3232.

Table 9.4 General characteristics of the centrality measures of the nodes in the envelope system

	Centrality measures		
	Degree centrality	**Closeness centrality**	**Betweenness centrality**
MEANS	**2.99**	**16.52**	**1065.42**
SD	**1.41**	**11.58**	**793.81**
SUM	**3232**	**17974.09**	**1159176**
VAR	**1.991**	**134.16**	**630146.15**
MIN	**1**	**0**	**0**
MAX	**19**	**26.77**	**1771**

9.5.1 Centrality measures of the significant components in the envelope system

This section of the research presents the centrality measures of the envelope system network, which were calculated using Gephi. The centrality measures applied are the degree centrality, closeness centrality and betweenness centrality. The nodes that will be investigated are the 10^{th} higher degree centrality nodes in the envelope system components, which are the most important nodes in the system. Table 9.5 indicates the centrality measures of the higher degree centrality windows in the envelope system.

The degree centrality of a window represents the number of architectural spaces that are connected to it as well as the number of windows that are connected to it. Each window in the building is connected to two windows and architectural spaces. Thus, the result of the highest degree window, which is F5W1AW1 with degree centrality of 19, indicates that the window is connected to 17 architectural spaces.

The results of closeness centrality and betweenness centrality indicate that there is no pattern between the degree centrality of the envelope system components and the closeness centrality and betweenness centrality.

Table 9.5 Centrality measures of the highest degree centrality windows in the envelope system

	Centrality measures		
Envelope system components	**Degree centrality**	**Closeness centrality**	**Betweenness centrality**
F5W1AW1	19	6.61	425
F5W1CW1	9	7.98	366
F4W1DW1	9	7.795	336
F5W1CW9	8	5.5	496
F4W1CW5	7	6.90	401
F4W1AW2	7	10.28	269
F5W1DW1	6	6.37	437
F1W1CW2	6	11.09	239
F1W1AW5	6	12.05	159
F5W1CW2	5	9.14	307

9.6. General characteristic of the HVAC system design network

Table 9.6 indicates the general characteristics of the centrality measures of the nodes in the HVAC system. The average degree centrality is 2.85, which are the average interactions between the nodes in the system. The closeness centrality is 0.31, which is a very low average of closeness centrality; this indicates that the network is a strongly connected one with very important nodes that are central in the network. The average betweenness centrality of the nodes in the HVAC system is 0.81, which indicates that a large number of nodes in the network are not located in the shortest path between the nodes. In addition, the nodes with the highest degree centrality of 36 in the HVAC system are B1FAN1 and B2FAN1. Theses nodes are the basement fans. When comparing the average degree centrality of all nodes in the HVAC system, which is 2.85, and the higher degree centrality, which is 36, it indicates that there are nodes that control the connectivity in the network with a high degree centrality; theses nodes are the supply ducts and the return ducts, which gather the architectural spaces in clusters. The highest closeness centrality of the HVAC system nodes is 1.97, for B1HVC2 and B2HVC2. The results indicate that HVAC rooms have the highest closeness centrality, which indicates that they are in the central location of the system. The highest betweenness centrality is 50, for B1FAN3 and B2FAN3. In addition, the standard deviation of degree centrality is 3.71, which indicates that the network has a large number of nodes with lower interactions, which are the nodes that are connected to the supply ducts and return ducts, which are the architectural spaces. The sum results indicate that the network nodes have the possibilities to interact 3422.

Table 9.6 General characteristics of the centrality measures of the nodes in the HVAC system

	Centrality measures		
	Degree centrality	**Closeness centrality**	**Betweenness centrality**
MEANS	**2.85**	**0.31**	**0.81**
SD	**3.71**	**0.58**	**3.88**
SUM	**3433**	**396.35**	**1019**
VAR	**13.77**	**0.339**	**15.03**
MIN	**1**	**0**	**0**
MAX	**36**	**1.97**	**50**

9.6.1 Centrality measures of the significant components of the HVAC system network

This section of the research presents the centrality measures of the HVAC system network, which were calculated using Gephi. The centrality measures applied in this network are the degree centrality, closeness centrality, and the betweenness centrality. The nodes that will be investigated are the 10^{th} highest degree centrality nodes in the network, which are the most important nodes in the system. Table 9.7 indicates the centrality measures of the higher degree centrality nodes in the HVAC system.

The degree centrality of a HVAC system component represents the number of components that are connected to it as well as the architectural spaces that are connected to it. The results indicate that the highest degree centrality nodes are B1FAN1 and B2FAN1 in the basements, which are connected to a large number of fans in the basements. In addition, the ducts with the highest degree centrality are F4DUCT1 with degree centrality of 24 and F4RDUCT1 with degree centrality of 23. This indicates that the duct and the return duct are connected to a large number of spaces to supply and return air from the architectural spaces.

The results of closeness centrality and betweenness centrality indicate that the closeness centrality of the higher degree centrality nodes is 1, which indicates that the nodes are central in the network. However, the betweenness centrality is changeable, with no similar pattern with the increases of the degree centrality.

Table 9.7 Centrality measures of the higher degree centrality nodes in the HVAC system

	Centrality measures		
HVAC system components	**Degree centrality**	**Closeness centrality**	**Betweenness centrality**
B1FAN1	36	1	35
B2FAN1	36	1	35
B1FAN4	27	1	26
B2FAN4	27	1	26
F4DUCT1	24	1	23
F4RDUCT1	23	1	0
F1DUCT1	21	1	10
F1RDUCT1	21	1	10
B1RFAN2	20	1	19
B2RFAN2	20	1	19

9.7. General characteristics of the power system design network

Table 9.8 indicates the general characteristics of the centrality measures of the nodes in the power system. The average degree centrality is 3.53, which are the average interactions between the nodes of the power system. In comparison to the maximum interacted node, which is F1CIRCU with degree centrality of 122, this indicates that there are significant nodes that are connecting the network components. The average closeness centrality is 0.33, which indicates that the nodes in the network are strongly connected with very important nodes that are central in the network. The results indicate the highest closeness centrality is 5.57, which is the result for F1G1, the generator that is connecting all the power system components and providing the electricity to the system. The average betweenness centrality of the power network is 3.47, which indicates the average times the node works as a bridge to connect two nodes through the shortest path; however, the highest betweenness centrality is 3857, which is a very large gap between the average the node with the highest betweenness centrality is the main panels room on the first floor, which provides electricity to all the panels rooms in the building from the generator. This indicates that there are important nodes that connect the system components together with higher betweenness centrality. In addition, the standard deviation of the degree centrality is 4.60; this indicates a large number of nodes with a low degree centrality and few nodes with a high degree centrality. The sum result of the degree centrality is 14248; this indicates the possibility of interactions in the network.

Table 9.8 General characteristics of the centrality measures of the nodes in the power system

	Centrality measures		
	Degree centrality	**Closeness centrality**	**Betweenness centrality**
MEANS	**3.53**	**0.33**	**3.47**
SD	**4.60**	**0.54**	**65.86**
SUM	**14248**	**1343.43**	**13995**
VAR	**21.23**	**0.30**	**4336.95**
MIN	**1**	**0**	**0**
MAX	**122**	**5.57**	**3857**

9.7.1 Centrality measures of the power system significant components

This section of the research presents the centrality measures of the power system network, which were calculated using Gephi. The centrality measures applied in this network are the degree centrality, closeness centrality, and betweenness centrality. The nodes that will be investigated are the 10^{th} higher degree centrality nodes in the network, which are the most important nodes in the system. Table 9.9 indicates the centrality measures of the higher degree centrality nodes in the power system.

The degree centrality of a power system component represents the number of components that are connected to it as well as the architectural spaces that are connected to this component. The results indicate that the highest degree centrality node of the power system components is F4PLN2, which is the main panels room on the fourth floor of the building. In addition, the results in the table indicate that the power system component with the highest degree centrality is main panels rooms, which are connected to the power lines that provide the architectural spaces' receptacles with electricity.

The results of closeness centrality and betweenness centrality of the higher degree centrality nodes indicate the main panels rooms are located in a central location in the network that is close to all nodes in the network; however, the betweenness centrality of the higher degree nodes indicates that the most important nodes are not located in the shortest paths between nodes, except one node, which is F1PLAN1, the first floor main panels room, with betweenness centrality of 3857.

Table 9.9 Centrality measures of the higher degree centrality nodes in the power system

	Centrality measures		
Power system components	**Degree centrality**	**Closeness centrality**	**Betweenness centrality**
F4PLN2	67	1.754578755	0
F1PLAN1	64	1.726027397	3857
F3PLN1	44	1.68115942	0
F5PLN1	39	1.734693878	0
F7PLN	34	1.817204301	0
F8PLN	34	1.817204301	0
F9PLN	34	1.817204301	0
F10PLN	34	1.817204301	0
F11PLN	34	1.817204301	0
F12PLN	34	1.817204301	0

9.8. General characteristics of the lighting system design network

Table 9.10 indicates the general characteristics of the centrality measures of the nodes in the lighting system. The average degree centrality is 3.67, which are the average interactions between the nodes of the lighting system. In comparison to the maximum interacted node, which is F1CIRCU with degree centrality of 390, this indicates that there are few significant nodes that are connecting the network components. The average closeness centrality is 0.15, which indicates that the nodes in the network are strongly connected with very important nodes that are central in the network. The results indicate that the highest closeness centrality is 1.96, which is the result for F5CM1, communications room number 1 on the fifth floor of the building. The average betweenness centrality of the lighting network nodes is 1.08 and the maximum betweenness centrality node is 48 for node F5LL29, which is lighting line 29 on the fifth floor. The betweenness centrality indicates that the average times the node works as a bridge to connect two nodes through the shortest path. This result indicates that the betweenness centrality average is low compared to the power system network. In addition, the standard deviation of the degree centrality is 8.94 and the maximum degree centrality is 390; this indicates that there are a large number of nodes with a low degree centrality and few nodes with a high degree centrality. The sum result of the degree centrality is 41102; this indicates the possibility of interactions in the networks.

Table 9.10 General characteristics of the centrality measures of the nodes in the lighting system

	Centrality measures		
	Degree centrality	**Closeness centrality**	**Betweenness centrality**
MEANS	**3.67**	**0.15**	**1.08**
SD	**8.94**	**0.38**	**4.11**
SUM	**41102**	**1630.27**	**12128**
VAR	**79.93**	**0.14**	**16.94**
MIN	**1**	**0**	**0**
MAX	**390**	**1.96**	**48**

9.8.1 Centrality measures of the lighting system significant components

This section of the research presents the centrality measures of the lighting system network, which were calculated using Gephi. The centrality measures applied in this network are the degree centrality, closeness centrality, and betweenness centrality. The nodes that will be investigated are the 10th higher degree centrality nodes in the network, which are the most important nodes in the system. Table 9.11 indicates the centrality measures of the higher degree centrality nodes in the lighting system.

The degree centrality of a lighting system component represents the number of components that are connected to it as well as the architectural spaces that are connected to this component. The results indicate that the highest degree centrality node of the lighting system components is F1PLAN1, which is the main panels room on the first floor with 66-degree centrality.

The results of closeness centrality and betweenness centrality of the highest degree centrality nodes indicate the main panels rooms are located in a central location in the network that is close to all nodes in the network with an average closeness centrality of 1.9 to the ten main panels rooms with higher degree centrality. The results of the betweenness centrality of the panels rooms in the lighting system indicates that the panels rooms in the lighting system are not working as a bridge in the shortest path between nodes in the lighting system.

Table 9.11 Centrality measures of the highest degree centrality nodes in the lighting system

	Centrality measures		
Lighting system components	**Degree centrality**	**Closeness centrality**	**Betweenness centrality**
F1PLAN1	66	1.89	0
F2PNL1	53	1.89	0
F5PLN1	53	1.92	0
B1PLN1	44	1.87	0
B2PLN1	44	1.87	0
F7PLN	38	1.93	0
F8PLN	38	1.93	0
F9PLN	38	1.93	0
F10PLN	38	1.93	0
F11PLN	38	1.93	0

9.9. Assessment of the building systems design resilience to certain design phenomena

This section of the research will assess the resilience of the building system components to several phenomena as well as indicating the effects of changes that happen in the system. It will use the centrality measures to determine the significant components of the system that are most influential in terms of the building system's resilience. The following section indicates the use of the centrality measures to assess the building system's resilience.

9.9.1 Assessment of the envelope system design resilience

This section of the research will investigate the resilience of the building envelope design in terms of the very significant factor that is taken into consideration when designing a building envelope system. This factor, which increases the complexity of the building envelope design, is the difficulty of providing the optimal natural lighting to the architectural spaces. The use of network modelling techniques will significantly enhance the efficiency of determining the natural lighting that is needed for each space in the building. Fig. 9.8 indicates the modelling of the windows' connectivity to the architectural spaces. As shown in Fig. 9.8, there are four groups of windows, which are W1A, W1B, W1C, and W1D. W1A are the windows that face north, W1B are the windows that face east, W1C are the windows that face south, and W1D are the windows that face west. This modelling technique can significantly enhance the efficiency of redesigning the layout of the building's architectural spaces based on the need for solar orientation of the spaces. The spaces that are required in the north elevation will be connected to the north windows and so on to the other elevations of the building. In addition, the degree centrality of the windows indicates the number of architectural spaces that are connected to it. F5W1AW1 is a window located on the fifth floor of the building and which faces north, as shown in Fig. 9.8. It has a 17-degree centrality, which indicates that it is connected to 17 architectural spaces.

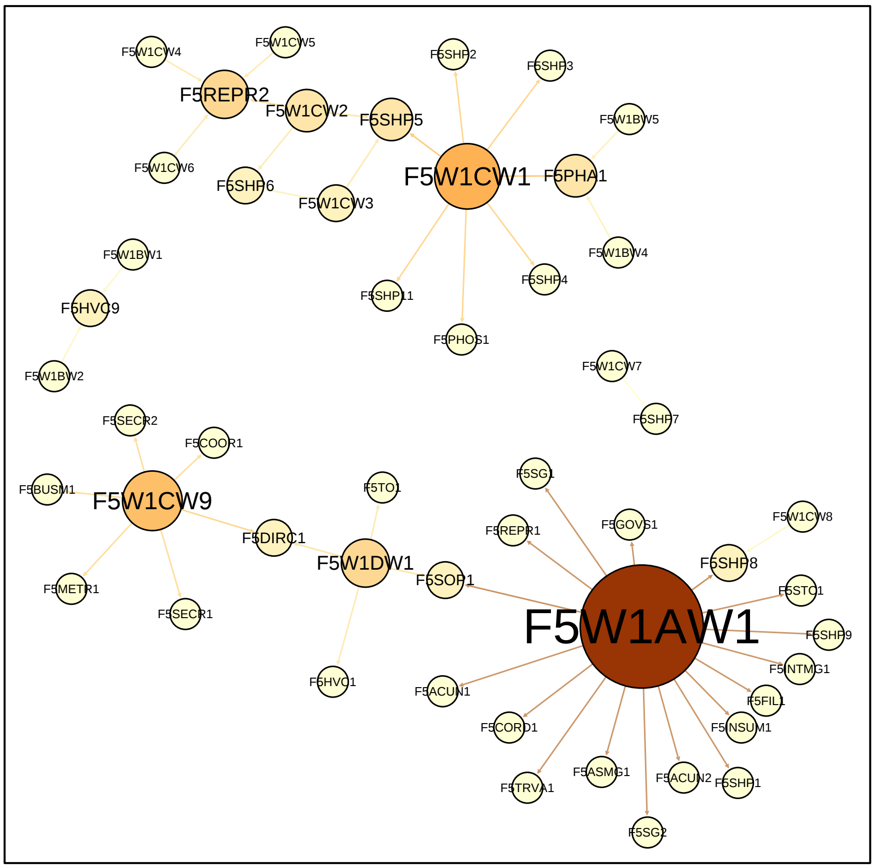

Fig. 9.8 Windows' connectivity to the architectural spaces

9.9.2 Assessment of the HVAC system design resilience

This section of the research investigates the resilience of the building's HVAC system design to a very significant factor that is taken into consideration when designing a building's HVAC system. This factor, which increases the complexity of the building's

HVAC system design, is the difficulty of determining the effect of a failure of a specific component of the HVAC system on the architectural spaces. The components of the HVAC system design consist of the HVAC rooms, the ducts that supply and return air, and the architectural spaces that are provided by the ducts. This section of the research will assess these components' resilience to failure of connectivity using one floor of the building, which is the third floor. Fig. 9.9 indicates the modelling of the interactions between the HVAC system components and the architectural spaces of the third floor of the building. As shown in Fig. 9.9, there are four ducts and four return ducts that supply the architectural spaces in the third floor of the building. Failure of one of these ducts to supply or return air will affect a number of architectural spaces. Table 9.12 indicates the results of the highest degree centrality ducts, which are duct number 3 and return duct number 3, with degree centrality of 18. This result indicates that the each of these ducts is connected to 17 architectural spaces and one HVAC room that provide the air from machines on the service floor. Fig. 9.10 indicates the change of the typology when F3DUCT3 is disconnected and fails to provide air. This failure of F3DUCT3 indicates that 17 architectural spaces will be affected, which is shown in Fig. 9.10.

Table 9.12 Highest degree centrality ducts on the third floor

Label	Degree	Closeness Centrality	Betweenness Centrality
F3DUCT3	18	1	17
F3RDUCT3	18	1	0

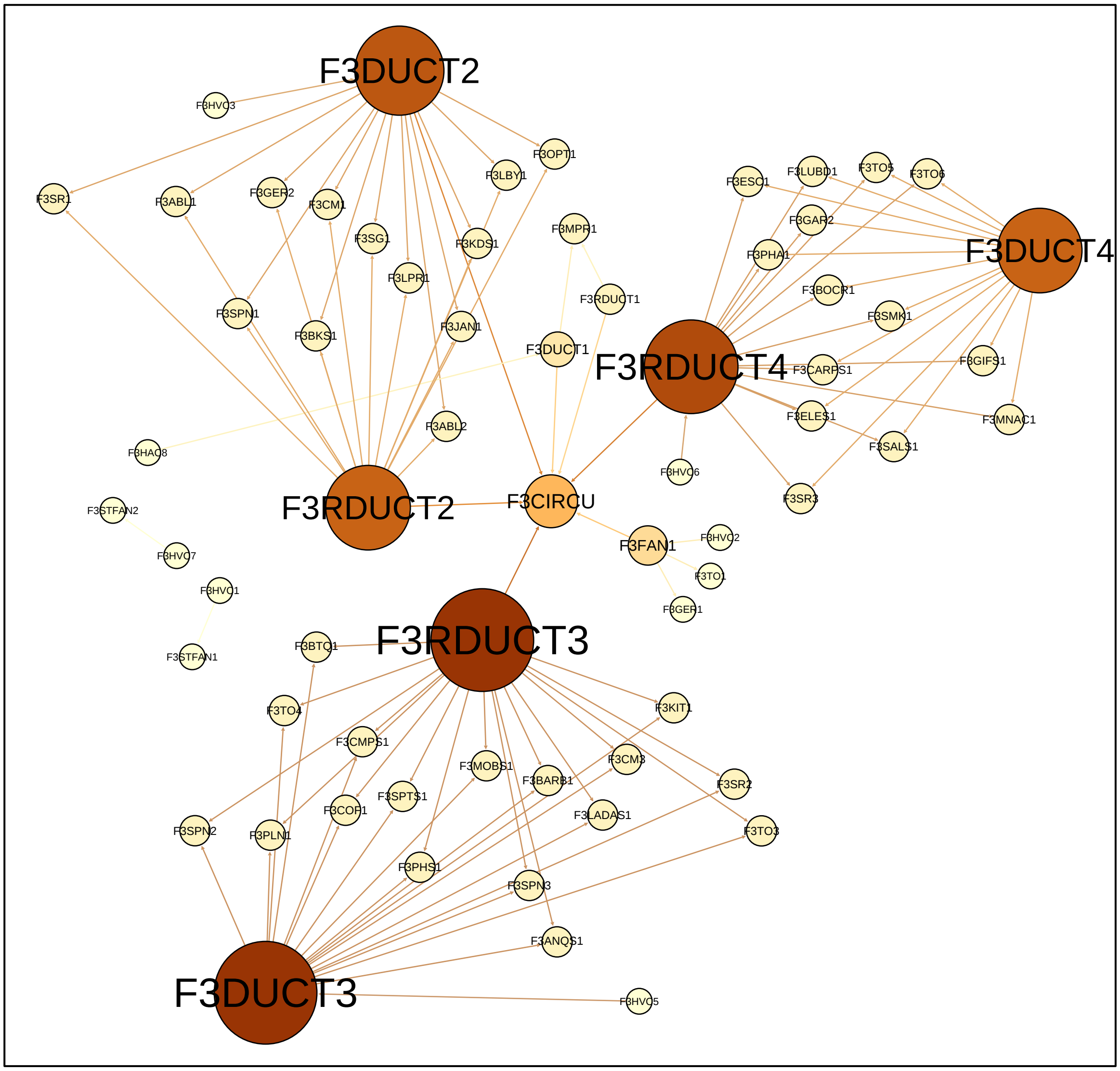

Fig. 9.9 Interactions between the HVAC system components and the architectural spaces of the third floor of the building

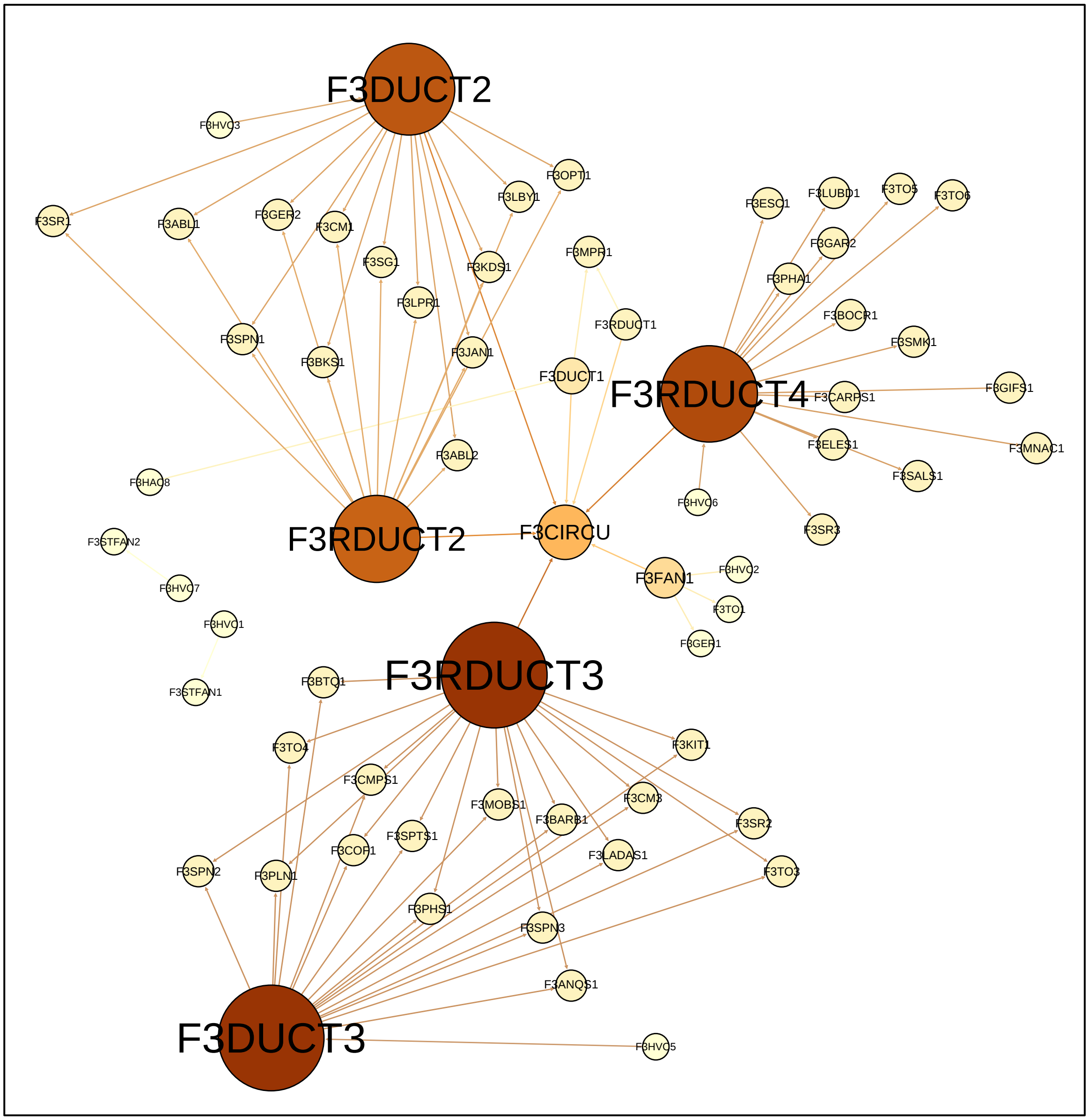

Fig. 9.10 Change of the typology when F3DUCT3 is disconnected and fails to provide air

9.9.3 Assessment of the power system design resilience

This section of the research investigates the resilience of the building's power system design to a very significant factor that is taken into consideration when designing a building power system. This factor, which increases the complexity of the building power system design, is the difficulty of determining the effect of a failure of a specific component of the power system on the architectural spaces. The components of the power system design consist of the main panels rooms, the power lines that are connected to the main panels rooms, and the receptacles. This section of the research will assess the power system components' resilience to failure of connectivity using one floor of the building, which is the seventh floor. Fig. 9.11 indicates the modelling of the interactions between the power system components and the architectural spaces of the seventh floor of the building. Fig. 9.11 shows the main panels room that is connected to 34 power lines that are located in the architectural spaces and provides the receptacles with electricity. If one of these power lines fails to supply the receptacles it will affect a number of architectural spaces. Table 9.13 indicates the results for the four highest degree centrality power lines on the seventh floor of the building, which are 9-degree centrality for F7PL27, F7PL17, and F7PL25 and 8-degree centrality for F7PL30. Fig. 9.12 indicates the typology of the interactions of F7PL27, which is power line 27 on the seventh floor. As shown in Fig. 9.12, F7PL27 is connected to the main panels room of the seventh floor which provides electricity to the floor's power lines and it provides seven receptacles with power, so the failure to provide this power line with electricity will result in the disconnection of seven receptacles of the floor's circulation space.

Table 9.13 Four highest degree centrality power lines on the seventh floor of the building

Label	Degree	Closeness Centrality	Betweenness Centrality
F7PL27	9	1	10
F7PL17	9	1	7
F7PL25	9	1	7
F7PL30	8	1	7

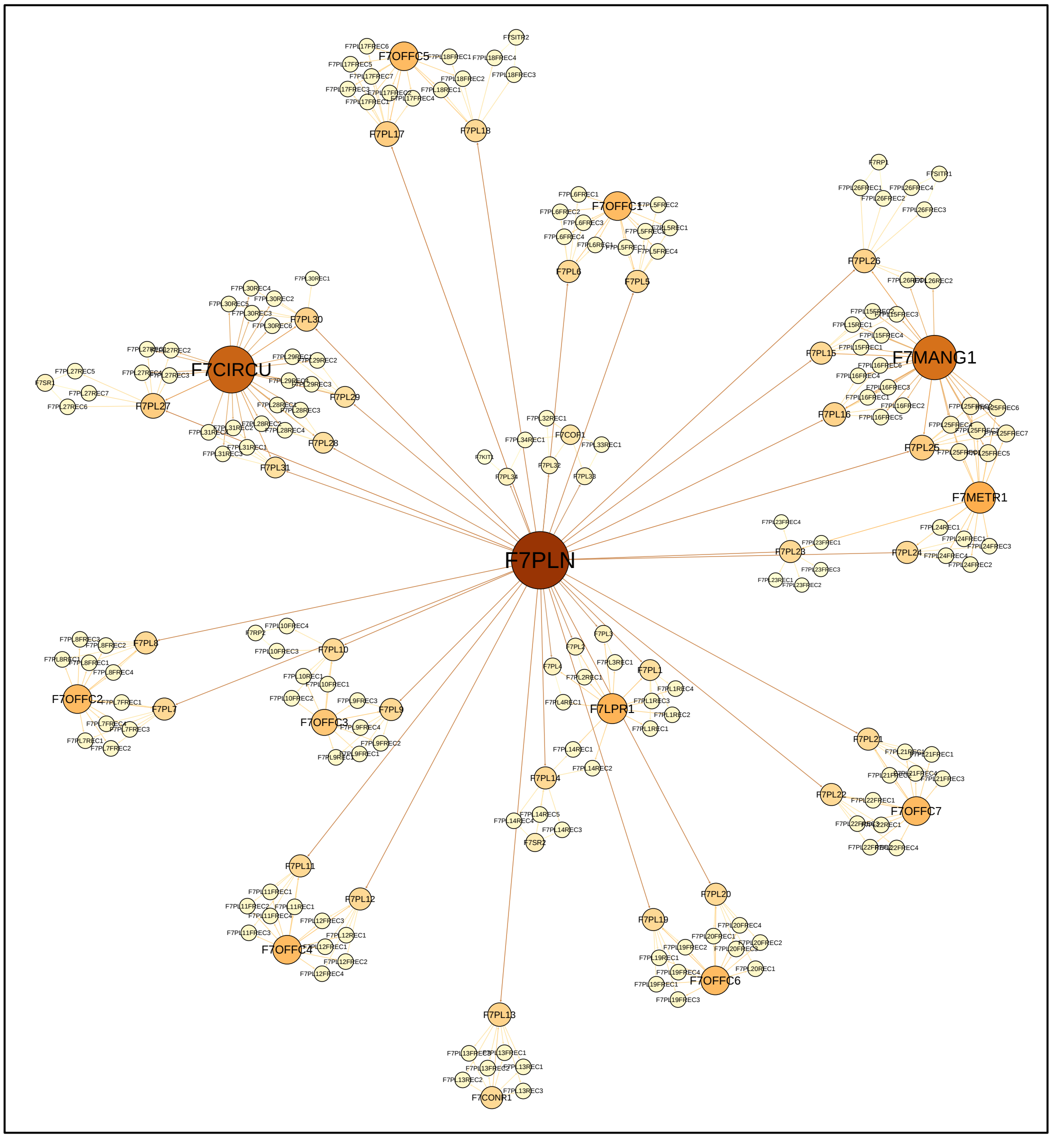

Fig. 9.11 Interactions between the power system components and the architectural spaces of the seventh floor of the building

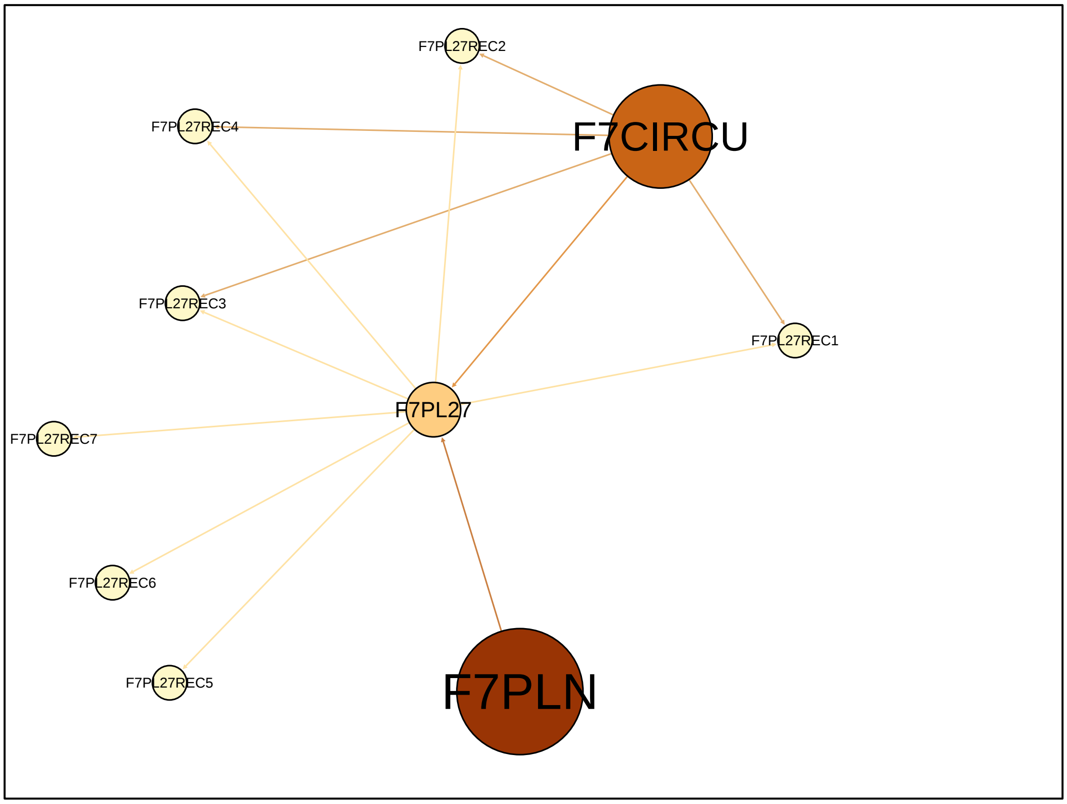

Fig. 9.12 Typology of the interactions of F7PL27, which is power line 27 on the seventh floor

9.9.4 Assessment of the lighting system design resilience

This section of the research investigates the resilience of the building's lighting system design to a very significant factor that is taken into consideration when designing a building's lighting system. This factor, which increases the complexity of the building lighting system design, is the difficulty of determining the effect of a failure of a specific component of the lighting system on the architectural spaces. The components of the lighting system design consist of the main panels rooms, the lighting lines that are connected to the main panels rooms, and the lighting fixtures. This section of the research will assess the lighting system components' resilience to a failure of connectivity t using one floor of the building, which is the seventh floor. Fig. 9.13 indicates the modelling of the interactions between the lighting system components and the architectural spaces of the seventh floor of the building. Fig. 9.13 shows the main panels room that is connected to the 38 lighting lines that are located in the architectural spaces and provide the lighting fixtures with electricity. If one of these lighting lines fails to supply the lighting fixtures it will affect a number of architectural spaces. Table 9.14 indicates the results of the six highest degree centrality lighting lines on the seventh floor of the building. Fig. 9.14 indicates the typology of the interactions of F7LL22, which is lighting line 22 on the seventh floor. As shown in Fig. 9.14, F7LL22 is connected to the main panels room of the seventh floor which provides electricity to the floor lighting lines and it provides 22 lighting fixtures with power, so a failure to provide this lighting line with electricity will result in the disconnection of 22 lighting fixtures in the floor's conference room.

Table 9.14 Six highest degree centrality lighting lines on the seventh floor of the building

Label	Degree	Closeness Centrality	Betweenness Centrality
F7LL22	24	1	22
F7LL13	23	1	21
F7LL2	22	1	22
F7LL16	22	1	20
F7LL11	21	1	28
F7LL24	19	1	18

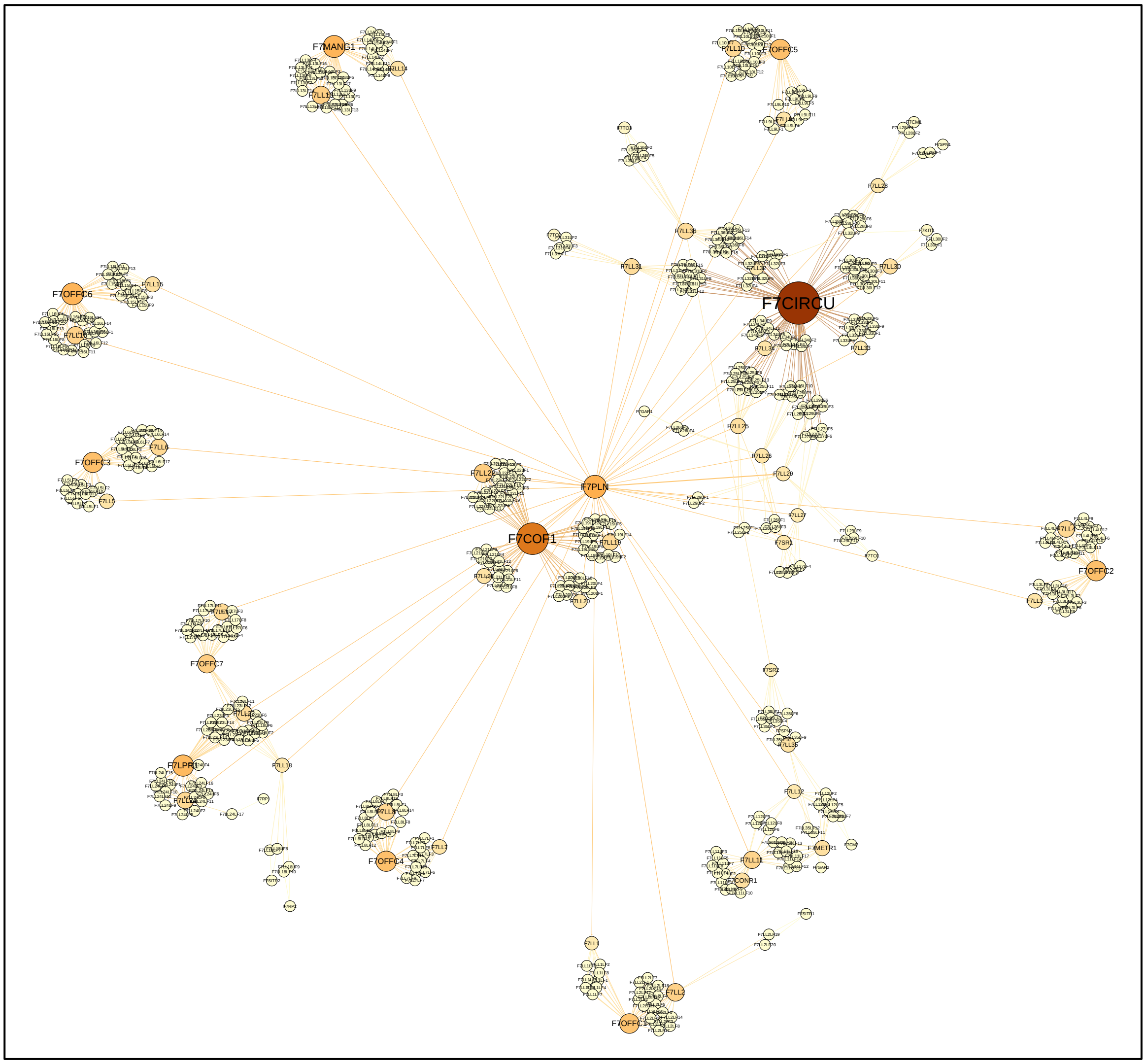

Fig. 9.13 Interactions between the lighting system components and the architectural spaces of the seventh floor of the building

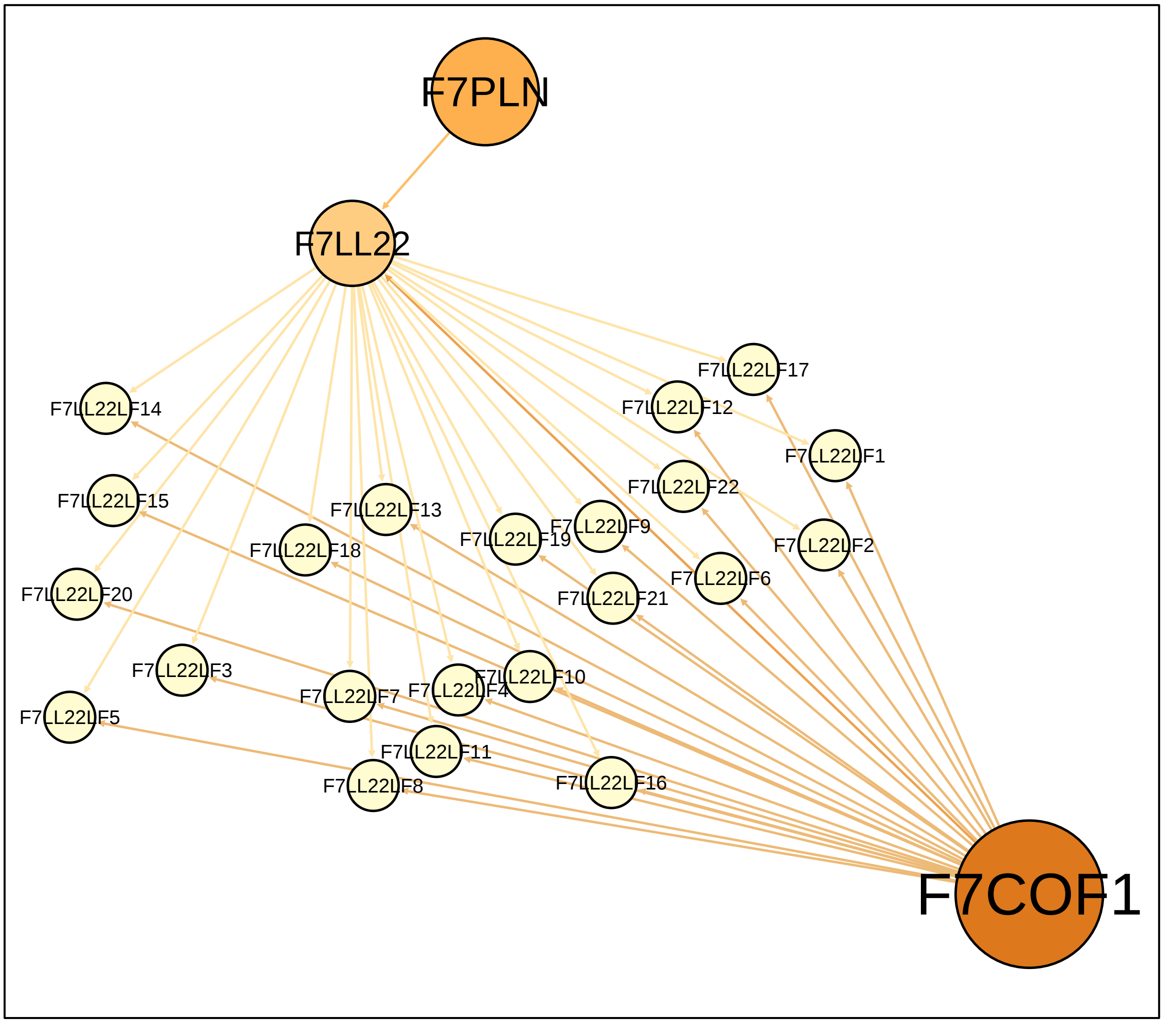

Fig. 9.14 Typology of the interactions of F7LL22, which is lighting line 22 on the seventh floor

9.10 Conclusion

This chapter of the research has uncovered the significant aspects of the building systems design complexity, which are the complexity of designing a resilient system such as envelope system, HVAC system, power system, and lighting system, and the assessment of these systems in relation to changes and disconnection of a system component. The chapter started with a descriptive analysis of the building case study indicating the system design layouts of the building and uncovering the typological characteristics of the building systems design, and providing an assessment of the resilience of the systems. The chapter has provided an explanation of the floor plan of the building systems as well as the interactions between the systems' components in the form of a network that is characterised by its typological findings. The chapter has also presented an assessment of the building systems' components in terms of their resilience to changes in the typology due to a disconnection of a system component. In addition, the use of centrality measures has indicated the importance of the components of the building systems in terms of their connectivity.

CHAPTER 10: DISCUSSION

10.1. Introduction

The aim of this research is to uncover the structure and the dynamic of building information interaction and propagation in the building design process and building systems design. This chapter will discuss the most important findings of this research, which are mainly focused on two aspects of building design complexity, the complexity of the building design process and the complexity of building systems design. This chapter will also present the answer to the research questions. It will discuss the significance of the scientific approach that is used to investigate the complexity of the building design process and building product, which is a complexity science approach. This chapter will also discuss the factors that increase the complexity of building design in terms of the process and the product that is established as a framework from complexity of building design. Moreover, the chapter will discuss the tool that has been used to model the complexity of building design and the value of using this tool to investigate complexity of design. Finally, the chapter will present the significant findings of the typological characteristics of the building design process and building product and the importance of the modelling to the field of building design, and will indicate the importance of using complexity modelling to enhance the efficiency of the design process knowledge diffusion as well as the design of resilient building systems.

10.2 The complexity of design

What is the scientific approach to uncovering the structure and the dynamic of building information and propagation in the building design process and product?

In order to uncover the structure and the dynamic of building information and propagation of building design, there has to be a scientific approach to follow. The uncovering of complexity in design in this research is determined by the modelling of the complex interactions between the building design process aspects as well as the interactions of the building systems' components. This interaction of the aspects in terms of information and connectivity highlights the need to capture this complexity in order to enhance the uncovering of it. The answer to the question of what is the scientific approach to investigate the complexity of design is indicated in one of the directions for investigating complexity. These directions are: Reductionist Complexity Science, which Cilliers (2001) has defined as an approach that seeks the principles of complex systems in nature; Soft Complexity Science, which Cilliers (2001) has described as the science that looks at complex systems from the idea of connectivity; Complexity Thinking, which investigates the thinking approach of a science such as management and economy; and Engineering Systems Complexity, which is defined and determined by Braha (1998); this approach looks at complex engineering systems from a modelling point of view to uncover their complexity and make them more easy to control. This approach specifically investigates the complexity of designed products as well as the process of designing in terms of the components' interactions and the information flow. As a result, this is the answer to the question that the research has determined in terms of choosing the approach to investigate the complexity of building design.

10.3 Factors increasing complexity in design

What are the factors that increase the complexity of the building design process and product?

From reviewing the literature on complexity in design, several researchers have agreed that design complexity is increasing as the amount of design information increases. According to Ralph's (2009) design process model, there are two dimensions of complexity in design, which are the complexity of establishing the design process components such as the specifications, agents, goals, requirements, primitives, and constraints, and the complexity of the whole process, which is indicated in the interactions of pieces of information to generate the components of the building design process in another meaning the complexity of the information flow through the design process. Alexiou (2009) described design complexity as an "indeterminism problem because it lacks the knowable complete set of beginning condition owning to endless amount of information that can be collected before beginning". This definition specifically identifies that there is complexity in establishing each component of the design. This complexity is determined in Suh's (2005) definition of design complexity, which is "the measure of uncertainty in understanding what it is we want to know or in achieving a functional requirement"; it indicates that achieving the functional requirements requires the uncertainty to be measured to indicate the complexity of a design. This research has classified the complexity of the building design process based on Ameri's (2008) research, which classifies complexity into three classes: the complexity of the design process, the complexity of the product, and the design problem. However, this research classified the complexity of design into two aspects, which are complexity of the design process, and complexity of the design product. In addition, this research has determined and modelled the factors that increase the complexity of the building design process based on reviewing several studies in the literature on building design process complexities as well as the factors that increase the complexity of building system design. Fig. 10.1 indicates the factors that increase the complexity of the building design process, which are divided into three groups: the factors that increase the complexity of building design process modelling, the factors that increase the complexity of establishing the building design process components, and the factors that increase the complexity of information interactions. The investigation, which is based on the RIBA plan of work of the process, is based on the third category of factors, the information interaction factors, which are the information flow and the knowledge diffusion. This research has focused on modelling and uncovering the complexity of the knowledge diffusion of the building design process based on the RIBA plan of work. In addition, Fig. 10.2 shows the complexity of building systems design, which is mainly focused on the resilience of the systems to phenomena and changes or failure of one of the system components. The systems modelled in this research are the architectural system, the structural system, the envelope system, the HVAC system, the power system, and the lighting system.

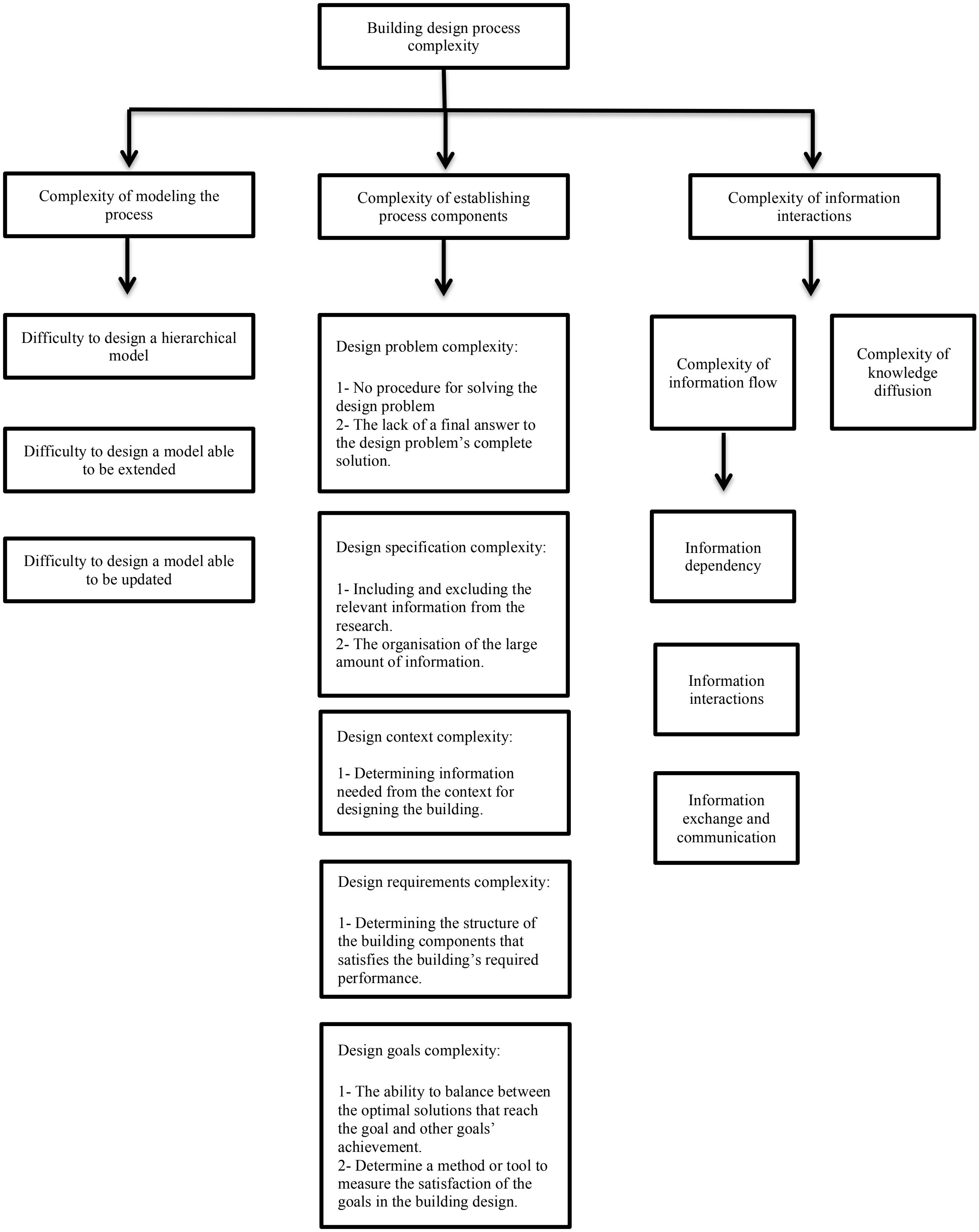

Fig. 10.1 Factors that increase the complexity of the building design process

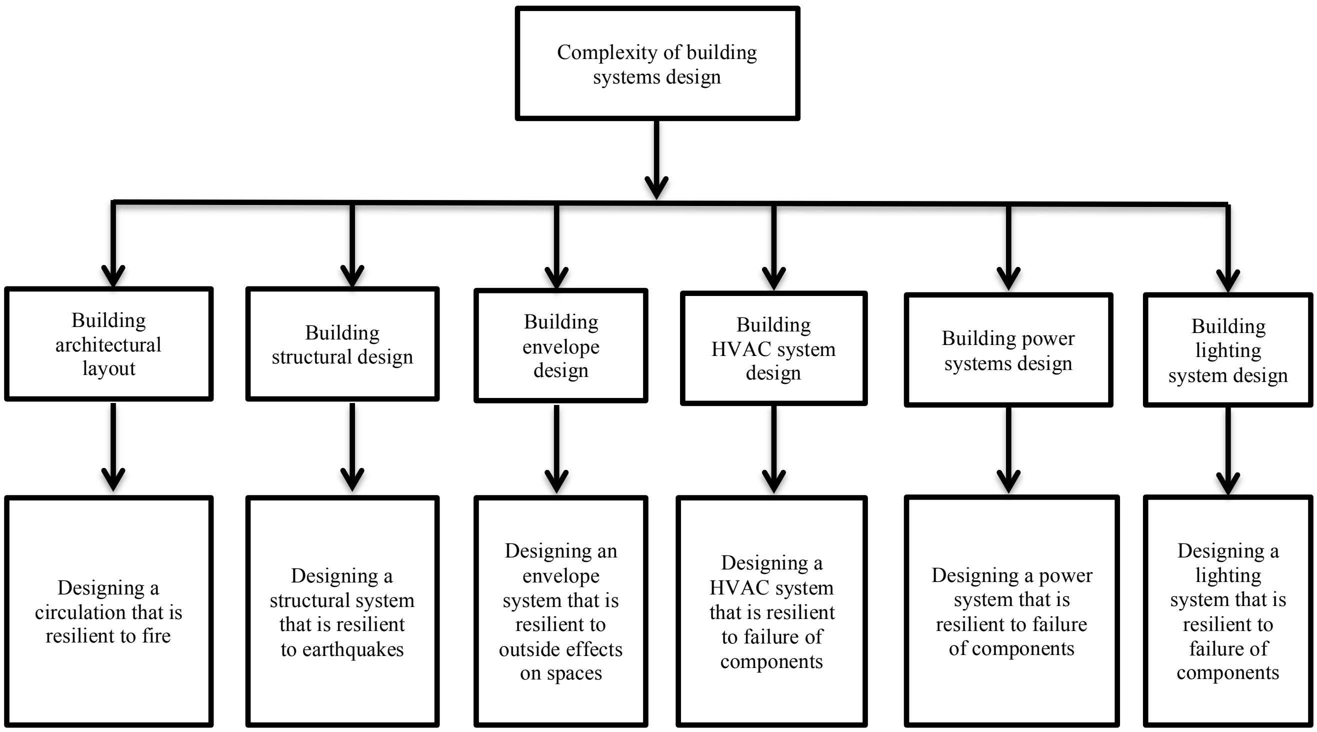

Fig. 10.2 Complexity of building systems design

10.4 The tool for investigating complexity in building design

What are the appropriate tools and the techniques for modelling complexity in the building design process and product?

The answer to the question is that the tools for investigating a large amount of information flow and large number of component interactions are network modelling techniques and measures. The research has focused on analysing and assessing the complexity of the knowledge diffusion in the building design process and the resilience of building systems design, which are the most influential factors that increase the complexity of the building design process and product. First of all, the diffusion of knowledge in the building design process is a very significant factor that is required to be analysed in order to assess the importance of the building design process. Following Austin (1999), the study has generated a model of information flow in the concept design stage as well as using the design structure matrix to establish the interactions of the design tasks with the design team. The research does not indicate a very significant aspect that is needed in the building design process, which is the outcomes of the design task, and also does not use further modelling techniques to indicate the paths of information flow or determine the significant design tasks based on the amount of information.

In order to investigate aspects of the building design process, this research has established significant modelling techniques, which are the modelling of the interactions between the design task, design team, and design process components using the design structure matrix to indicate the flow of information, and the network modelling techniques to indicate the typological characteristics of design stages and assess the important roles in the network stages in terms of information flow in the stages and controlling knowledge in them. Furthermore, the research has focused on analysing and assessing the resilience of the building system design.

The combination of both design structure matrix and network modelling techniques has significantly enhanced the efficiency of modelling the interactions and information flow in the aspects of the building design process, as well as the modelling of the building system components' interactions. Furthermore, the method of design structure matrix and network modelling has enhanced the efficiency of determining the significant components of knowledge diffusion in each stage of the building design process, and has also enhanced the efficiency of determining the significant components that play a role in designing a resilient building system. Moreover, the use of network measures has enhanced the efficiency of determining the significant components in terms of knowledge diffusion in each design process stage. The use of network measures has significantly assessed the resilience of the building system design to several architectural phenomena such as failure of components of the building system.

10.5 Theoretical approach to modelling complexity in building design

What is the theoretical approach that determines how to model complexity of the building design process and product?

The approach to modelling the complexity of building design requires the aspects of each of the processes and the product to be determined. In this research, the investigation and modelling of the building design process is based on the modelling of the main three aspects of it that receive and deliver information, which are the design team, design tasks and design process components. The finding of the relation between the three aspects of the process is used to model the flow of information and the knowledge diffusion in the building design process. The investigation and the modelling of the building systems design are based on the interactions between the components of the systems. The following is the approach to investigating and modelling the building systems design. First, one of the systems that the research has assessed the resilience of is the architectural layout design. Following Puusepp (2011), the research has determined the need to investigate the flow of circulation within the building layout from an approach of designing this flow to be suitable for the relations between the architectural spaces, which is a technique that is mainly used in designing architectural layouts. However, in this research the method used to model and assess the interactions of the building's architectural spaces is an advanced technique that significantly enhances the efficiency of dealing with a large amount of architectural space because it models the interactions between the spaces that are required to be close to each other as a network, and indicates the centrality measures of the architectural spaces as well as the circulation spaces. These centrality measures have enabled us to determine the most significant architectural spaces that are required to be central in the layout of the building design, which provides a significant design guide to generate the design of the building layout. In addition, this method of modelling architectural spaces as a network significantly helps the circulation flow design, and to investigate the fire escape design of the building layout because the designers can use the centrality measures of the architectural spaces to determine the location of the fire escapes in the building layout based on the importance of the architectural spaces as well as the degree and closeness centrality of the spaces.

Second, the research has also analysed and assessed the structural system; this system is a very important one in building design because it is the skeleton that holds the building together and protects it from outside effects. An important significant factor when designing the structural system of a building is its resilience to earthquakes and wind. According to Gunel (2007), earthquakes and wind are the most important aspects that need to be taken into consideration when designing the structural system of a building. Moreover, the study has classified the structure of tall buildings into three classes, which are steel, reinforced concrete, and composite. All of the buildings are required to be highly resilient to earthquakes.

Structural engineers are required to determine the effect of a failure of a component in the building's structural design when an earthquake happens. Thus, this research has presented a method of modelling the interactions of the structural system's components as a network, which significantly helps to indicate the propagation of the failure of a one component of the structural system onto other structural components. This can significantly enhance the efficiency of designing a structural system by reducing the number of components that are going to be affected when a certain component is affected by an earthquake.

Third, the research has also assessed the resilience of the envelope system's design. According to Ted J. and Kesik, B (2015), the significant aspects in designing an envelope system are its resilience to several phenomena: controllability of the thermal flow, controllability of airflow, moisture flow, sounds transmission, and fire resistance. The research has determined the factors that are most important to be taken into consideration when designing an envelope system; however, there has to be a technique for determining the effects of these phenomena on a specific architectural space. This can be indicated using the network modelling techniques, which the research has presented, by modelling the interactions between the architectural spaces of the building and the building envelope components. These modelling techniques offer a variety of ways to analyse the building system; however, this research has presented solar orientation of the architectural spaces using the network modelling techniques. This techniques has enhanced the ability to design a resilient envelope system for the building that can provide the optimal lighting required for each architectural space by locating the architectural spaces that require lighting to be from north in the north elevation, and the architectural spaces that require another elevation can be oriented and linked to another envelope system component.

Fourth, the fourth, fifth and sixth systems that the research has analysed and assessed in terms of resilience are the HVAC, power, and lighting systems. Using network modelling, the research has established a model of the HVAC system components' interactions with the architectural spaces, the power system components' interactions with the architectural spaces, and the lighting system components' interactions with the architectural spaces. These models significantly indicate the HVAC system's resilience by determining the effect of the failure of any of the HVAC system's ducts to the architectural spaces. This method is also applied for the power and lighting systems to indicate the effect of the failure of one component on the architectural spaces. These modelling techniques can significantly enhance the efficiency of designing a building's HVAC, power, and lighting system by indicating the effect of the components on architectural spaces. This can help designers to reduce the amount of effort required when designing one of these systems by not designing a very central component that can affect a large number of spaces in the building if it is disconnected from the HVAC, power, or lighting systems.

As a result, this section of the research has contributed to the knowledge on building design by classifying the complexity of building design in to process and product, as well as determining the most influential aspects that increase the complexity of building design. These factors that increase the complexity of building design can be analysed and assessed using several methods and techniques. However, what this research has applied to analyse the most influential factors, which are the knowledge diffusion in the process and the resilience in the building design process, is the combination of design structure matrix and network analysis techniques. According to Pektaş (2006), the complexity of building design has increased, which has forced professionals in the building design process to improve their tools for modelling the building design process. However, the design structure matrix on its own does not show the complexity of information and components' interactions due to the increased number of interactions. This research has combined two significant methods to complex and uncovered the complexity of building design process interactions as well as the building system design. This method generates networks that models that flow of information in the design process as well as modelling the interactions of building systems' components. These models capture the typological characteristics of the information flow and diffusion of knowledge in the building design process as well as the typological characteristics of building systems design.

10.6 The typological characteristics of the building design process

What are the typological characteristics of the building design process?

One of the significant objectives of the research is to model the interactions between the three main aspects of the building design process, which are design tasks, design team, and design process components, in the form of networks – each stage as an independent network that is characterised by its typological findings. Thus, the research has modelled each of the design process stages based on the RIBA plan of work aspects; the design tasks, design process components and the team required to establish the design tasks were all extracted from the plan of work. In addition, the research has modelled the flow of information between the three aspects in the form of networks. The networks that were generated are the strategic and brief stage network, preparation and brief stage network, the concept design stage network, the developed design stage network, and the technical design stage network. The modelling of the design process stages is the first step to answer the question regarding what are the typological characteristics of the building design process; the second step is to indicate the findings of the generated typologies.

The following section indicates the significant findings from the analysis of each of the design process stages. The typological characteristics of the design process stages' networks that have been established are the typology of the information flow in the networks and the results of calculating the centrality measures of the networks' nodes of the building design process. Table 10.1 indicates the number of edges and the number of nodes in each of the design process stages. As shown in the table, the nodes are the aspects of the design process and the edges are the information path between the edges. The results indicate that the number of nodes for each stage represents sources of information; the number increases as the design processes proceeds. However, the number of edges, which represents those paths of information flow, increases until the concept design stage and starts to decrease in the next stages. This indicates that the information flow has its highest interactions in the concept design stage and this is the highest stage in terms of the amount of knowledge diffused. In addition, Table 10.2 indicates the findings of the mean results of centrality measures for the network for each of the design process stages. The results indicate that the concept design stage aspects have the highest degree centrality with 4.82, which signifies that the concept design has the largest amount of information flowing and being delivered to the aspects of the building design process. Moreover, the closeness centrality results for the concept design indicate that the nodes aspects of the concept design are well connected because they result in a 2.07 closeness centrality, which is the lowest result for the stages after the strategic definitions, which are very low, so they are closest to each other. Furthermore, the research indicates that the significant design tasks and the most central design tasks that need to be taken into consideration in the concept design stage are S2T34 and S2T36. These design tasks are the cost consultant's task of assisting the lead designer to prepare the stage design programme and the development of the health strategy by the health and safety advisor. In addition, as shown in Table 10.3, the results of the degree centrality of all the design team members in the concept design stage indicate that the architect has the highest degree centrality, which means s/he is connected to a large number of information paths in the design stage. Fig. 10.3 indicates the location of the architect in the concept design stage network. Moreover, the concept design drawings resulted in a 17-degree centrality in the concept design stage as the highest design process component result of degree centrality in the design stage. Fig. 10.3 indicates the location of the concept

Design process stages	Number of nodes	Number of edges
Strategic definitions stage	52	82
Preparation and brief stage	49	100
Concept design stage	66	159
Developed design stage	64	146

Technical design stage	66	146

design drawings in the concept design stage network.

Table 10.1 Number of edges and number of nodes in each of the design process stages

Table 10.2 Means results of centrality measures for the network in each of the design process stages

	MEANS				
Centrality measures	**Strategic brief**	**Preparation and brief**	**Concept design**	**Developed design**	**Technical design**
Degree	**3.21**	**4.08**	**4.82**	**4.56**	**4.42**
Closeness	**1.27**	**2.22**	**2.07**	**2.53**	**2.63**
Betweenness	**2.4**	**18.77**	**23.45**	**41.34**	**30.84**

Table 10.3 Architect centrality measures

Design team member	**Concept design stage**		
	Degree centrality	**Closeness centrality**	**Betweenness centrality**
Architect	**16**	**1.82**	**90**

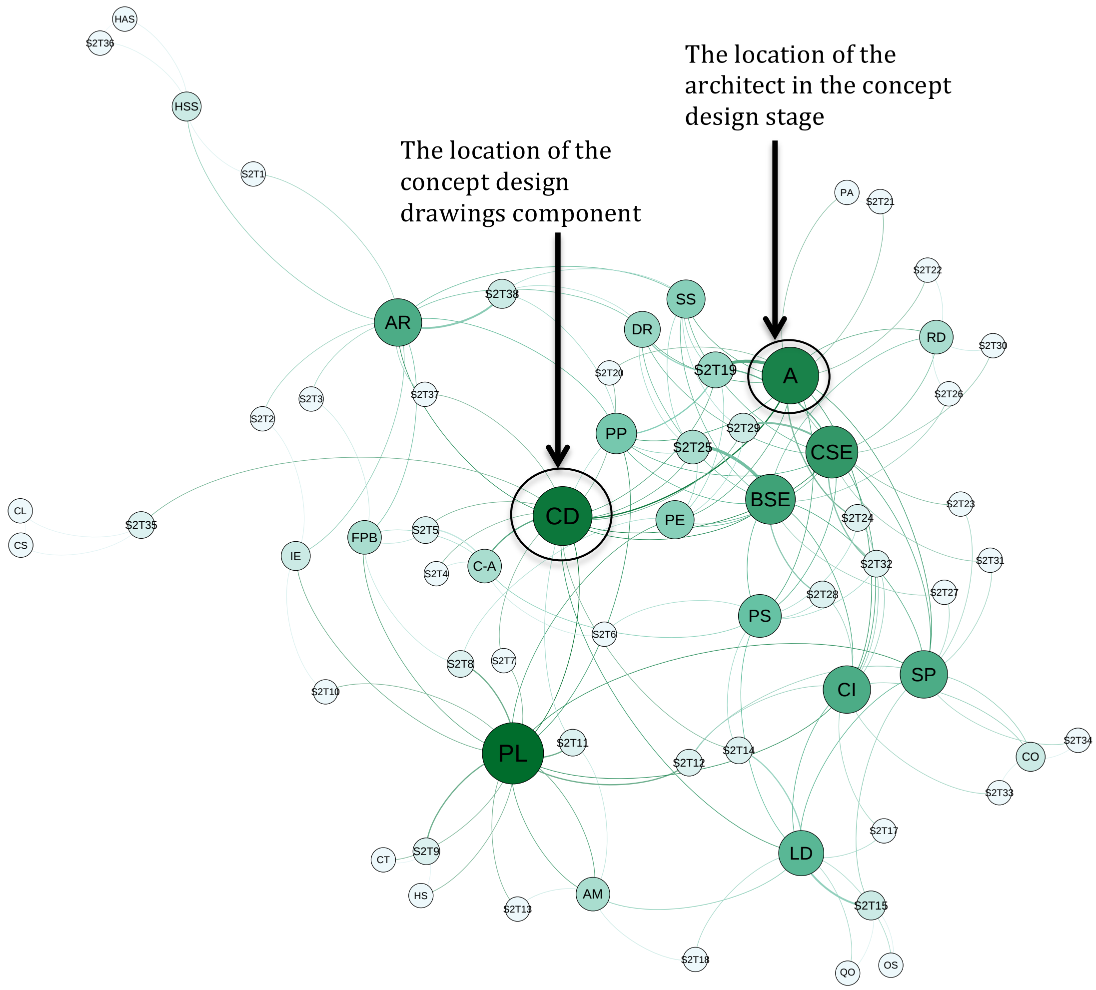

Fig. 10.3 Location of the architect in the concept design stage network

10.7 The significant aspects of knowledge diffusion

What are the significant aspects of knowledge diffusion in the building design process?

The importance of the knowledge diffusion investigation indicates how the network modelling of a design process stage can significantly enhance the efficiency of predicting the failure to deliver knowledge about a certain component of the process as well as the failure of a certain design team member to deliver knowledge. Thus, Fig. 10.4 indicates the fragility and the changes of the typology of the concept design stage network when information does not flow to and from the architect and when the architect does not deliver information required in this stage. The effect of disconnecting the architect in the concept design stage network will significantly affect the outcomes of the whole stage, not only that concept design drawing. The design process and the design task that will be affected are shown in Fig. 10.2, which consists of several pieces of information that flow from the architect to the establishment of the design task, which passes information to the concept design process component, which is the concept design drawings.

Furthermore, in the assessment of knowledge diffusion in the building design process, this section of the research will indicate the significant findings from modelling the typological characteristic of the building design process stage. Combining all the aspects of the building design process stage into one network will significantly demonstrate the findings concerning complexity of building design process knowledge diffusion as a whole network of information flow. This section of the research will discuss the combination of all the aspects of the design process stage as one network as well as indicating the results of the significant design tasks, design process components and design team members working in all the design process stages. Fig. 10.5 indicates the typology of information flow of the five design processes combined as a network. This section of the research has identified the centrality measures of the building design process network for each of the design process components, design process tasks, and design team members to indicate the importance of each aspect of the design process in the whole design process.

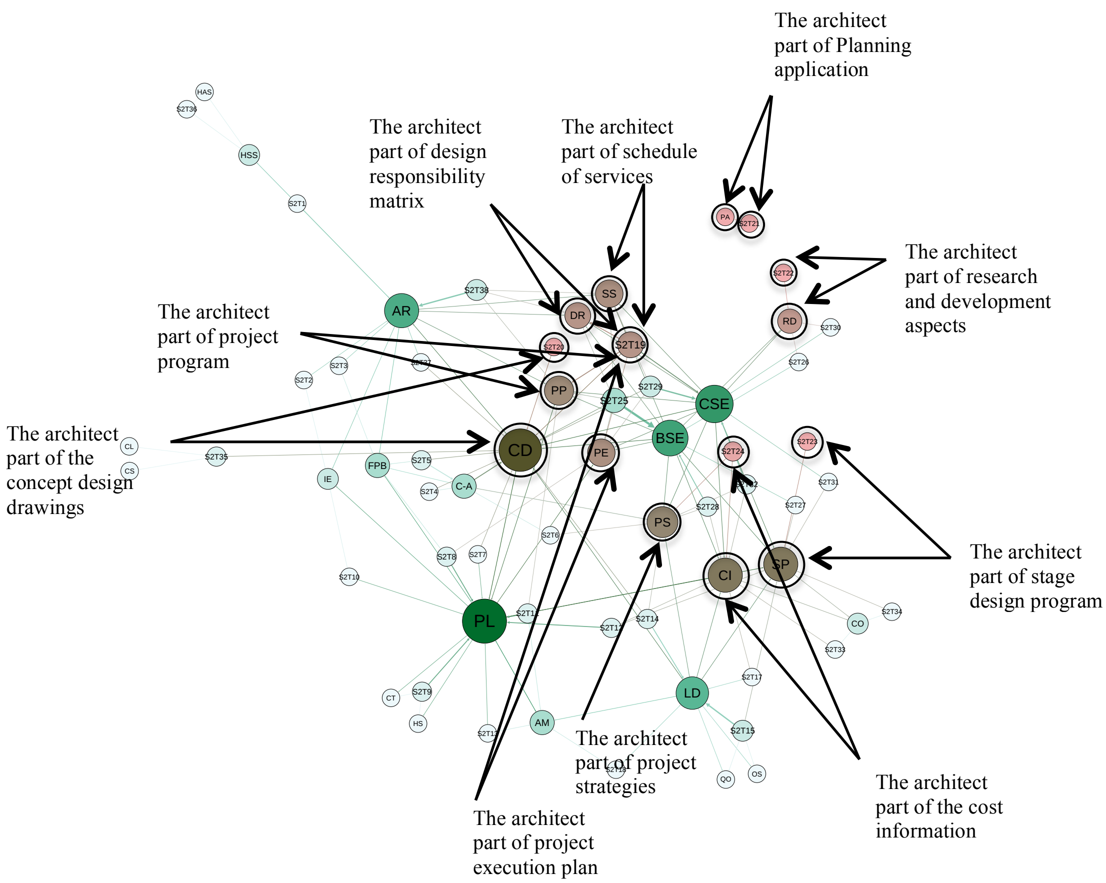

Fig. 10.4 Fragility and changes of the typology of the concept design stage network

Fig. 10.5 indicates the results of the degree centrality of the whole design process; as shown, the project lead has the highest degree centrality with 65, which indicates the importance of the project lead from the strategic definitions stage to the technical design stage. Fig. 10.6 indicates the order of the team members' importance in terms of the amount of information they deliver; the higher the degree centrality of a design team member, the larger the amount of information that s/he delivers and contributes to the establishment of design process components and tasks. Fig. 10.7 demonstrates the closeness centrality results for the design team members for the whole design process; the results indicate that, the lower the closeness centrality, the more central the design team member is in terms of delivering information. Thus, the closeness centrality of the significant design team members, such as the project lead, who are involved in the delivery of a large amount of information, is indicated as one of the lower closeness centralities, which makes the project lead a very central node in terms of delivering information in the whole design process. Moreover, Fig. 10.8 indicates the results of degree centrality of all the design process components in the whole design process stages combined. The results show that the project programme is the design process component that is receiving the most information from the design team members in the whole design process, with a degree centrality of 27. In addition, as shown in Fig. 10.9, the closeness centrality results for the design process components in the whole design process network of information flow indicate that the project programme resulted in 2.06, which is the lowest result of all the significant components with a higher degree centrality. This demonstrates that the project programme is very central in the network of the whole design process stages and reachable for all the design team members to deliver information to from the shortest paths of information flow.

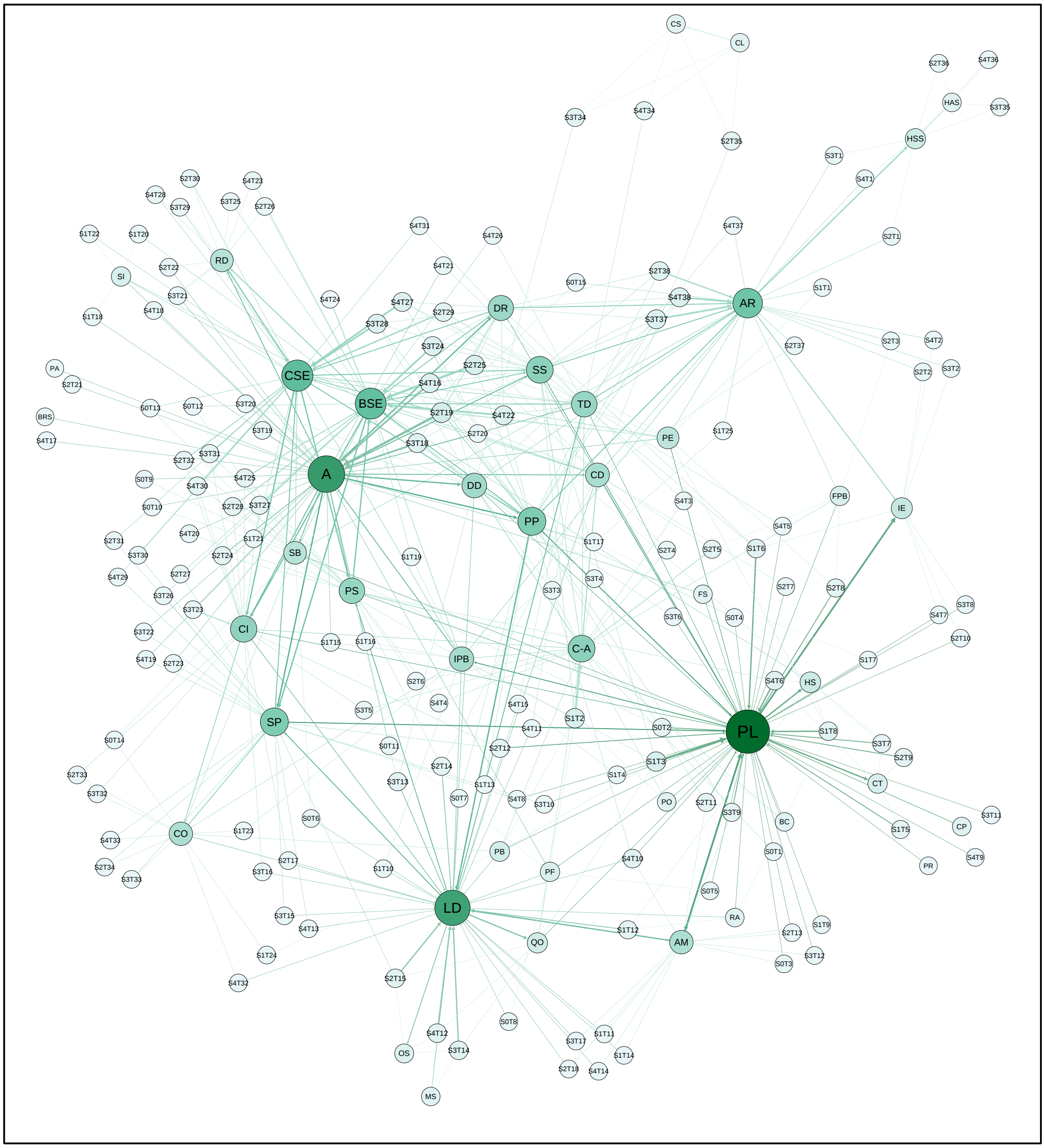

Fig. 10.5 Typology of information flow of the five design processes combined as a network

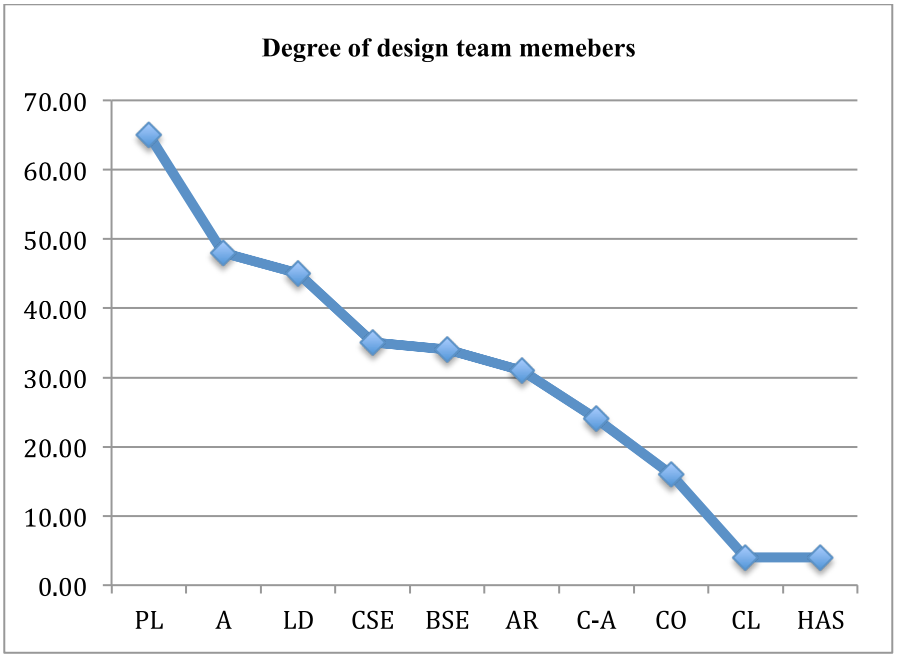

Fig. 10.6 Order of the team members' importance in terms of the amount of information they deliver

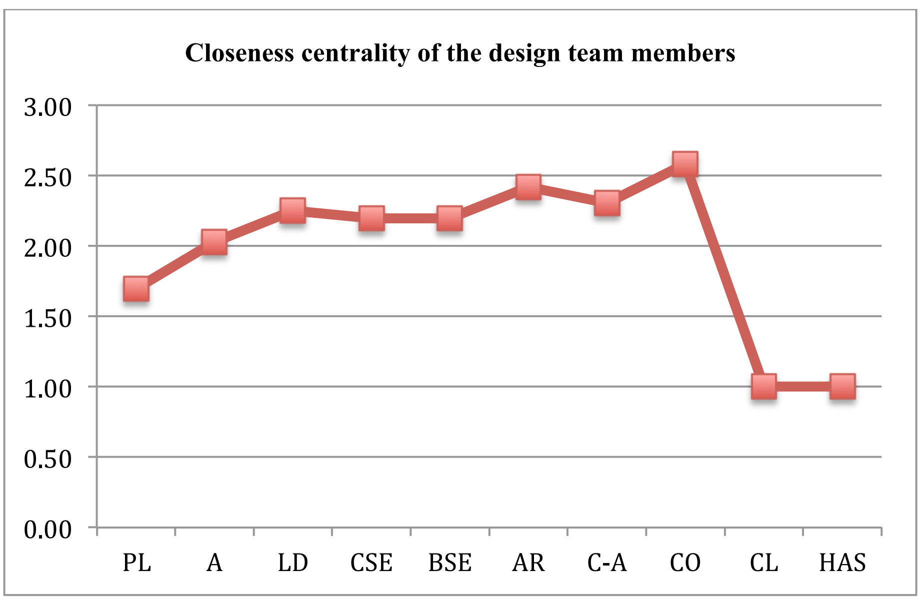

Fig. 10.7 Closeness centrality of the design team members in the whole design process

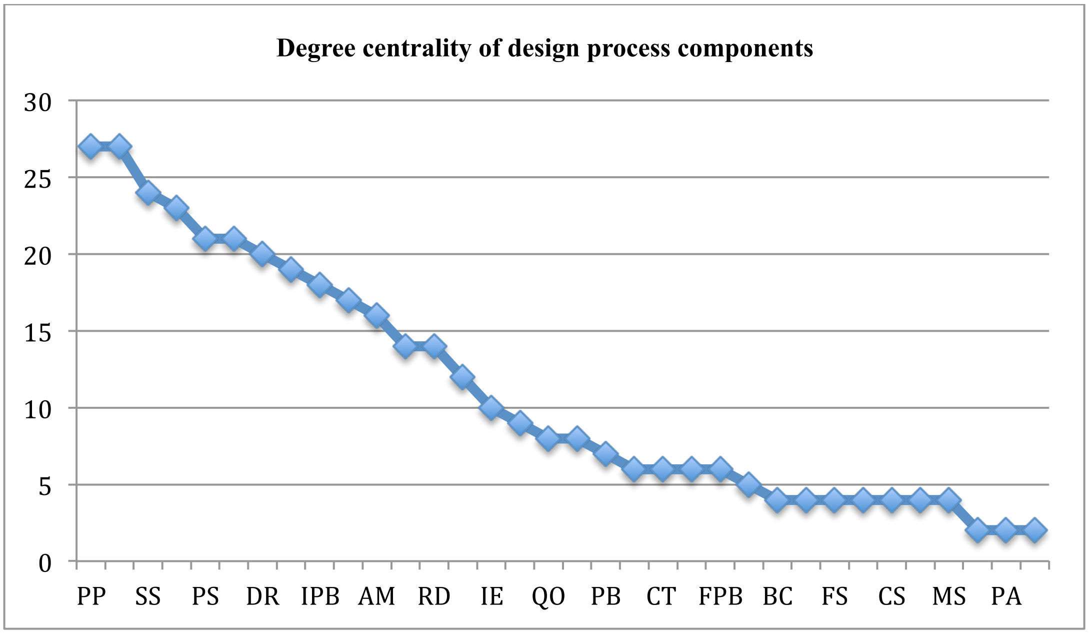

Fig. 10.8 Degree centrality of all the design process components in the whole design process stages combined

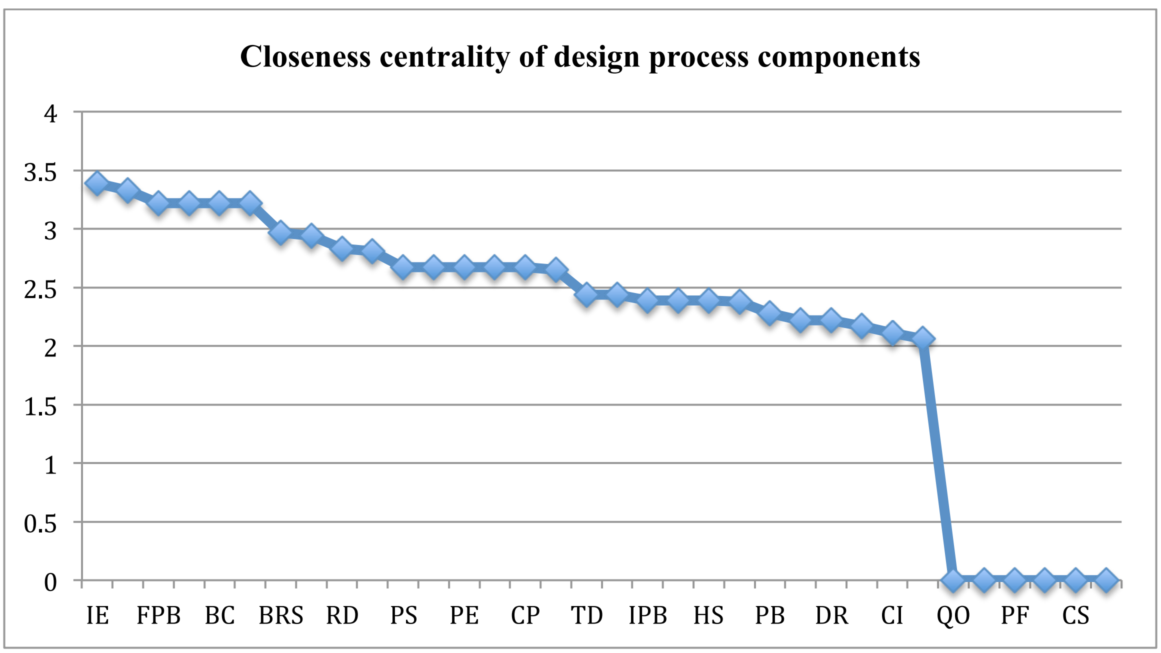

Fig. 10.9 Closeness centrality of the design process components in the whole design process information flow network

10.8 The typological characteristics of building systems design

What are the typological characteristics of building systems design?

One of the significant objectives of the research is to model the interactions between the building systems components in the form of networks. Each network represents a building system that is characterised by its typological characteristics. Thus, the research has modelled each of the building systems based on the interactions of components in a building case study. In addition, the research modelled the interactions between the architectural spaces and their circulation spaces, the interactions between the structural system components, the interactions between the envelope system components and the architectural spaces, the interactions of the HVAC system components, which represents the flow of air in the building, the interactions of the power system components, which represents the flow of electricity in the building, and the interactions of the lighting system components, which represents the flow of electricity in the lighting system of the building.

This section of the research discusses the significant findings for the building systems design. The typological characteristics of the building systems networks that have been established are the typologies of the interactions and flows of the building components, and the results of calculating the centrality measures of the networks' nodes are the components of the building systems. Table 10.4 shows the number of edges and the number of nodes in the design of each of the building systems, which indicates the relations between the number of components and the number of edges, which are the connections between the components. In addition, Table 10.5 displays the results of the means of each building system's centrality measure. The results indicate the relation between the degree centrality average of each system's components and the average of the closeness and the centrality measures. As the number of degrees increase, it indicates that the interaction of the system components is very high, and, as the closeness increases, it indicates the system components are far away from each other and in the form of clusters. In addition, the betweenness centrality gives an indication of how well the nodes are connecting the other nodes in the network; as the number decreases it indicates that either a large node is taking control of the whole network flow or there is a large path between the nodes of the network. Furthermore, the findings of this research indicate the significance of assessing the resilience of the components in each of the building systems based on several phenomena that occur in each of the building systems and which the systems are meant to resist.

Table 10.4 Number of edges and number of nodes in the design stage of each of the building systems

Design process stages	Number of nodes	Number of edges
Architectural design	1022	2101
Structural design	2146	4940
Enveloped design	1088	1626
HVAC system design	1245	1772
Power system design	4034	7124
Lighting system design	11199	20551

Table 10.5 Means for centrality measures in each of the building systems

Centrality measures	MEANS					
	Architectural design	Structural design	Enveloped design	HVAC system design	Power system design	Lighting system design
Degree	4.11	4.60	2.99	2.85	3.53	3.67
Closeness	11.44	3.40	16.52	0.31	0.33	0.15
Betweenness	770.48	345.19	1065.42	0.81	3.47	1.08

10.9 The significant aspects of a building system's resilient design

What are the significant aspects of designing resilient building systems?

The research investigated the resilience of each of the building system components and presented a method of assessing the resilience of each system to certain phenomena. These phenomena in architectural design are the design of a functional building layout with the ability to generate a good form of functional spaces and the design of a layout that is resilient to a fire. Fig. 10.6 indicates the flow of circulation if there is a fire. The use of network analysis has demonstrated the ability to assess the building design's resilience to fire, as well as the use of centrality measures has indicated the importance of those architectural spaces in terms of fire escapes. Fig. 10.7 shows the disconnection of one two corridor on the eighth floor of the building. Fig. 10.8 shows the disconnection of two stairs and indicates the alternative stairs that are used to escape from fire in the basement to the first floor and from the second floor to the first floor.

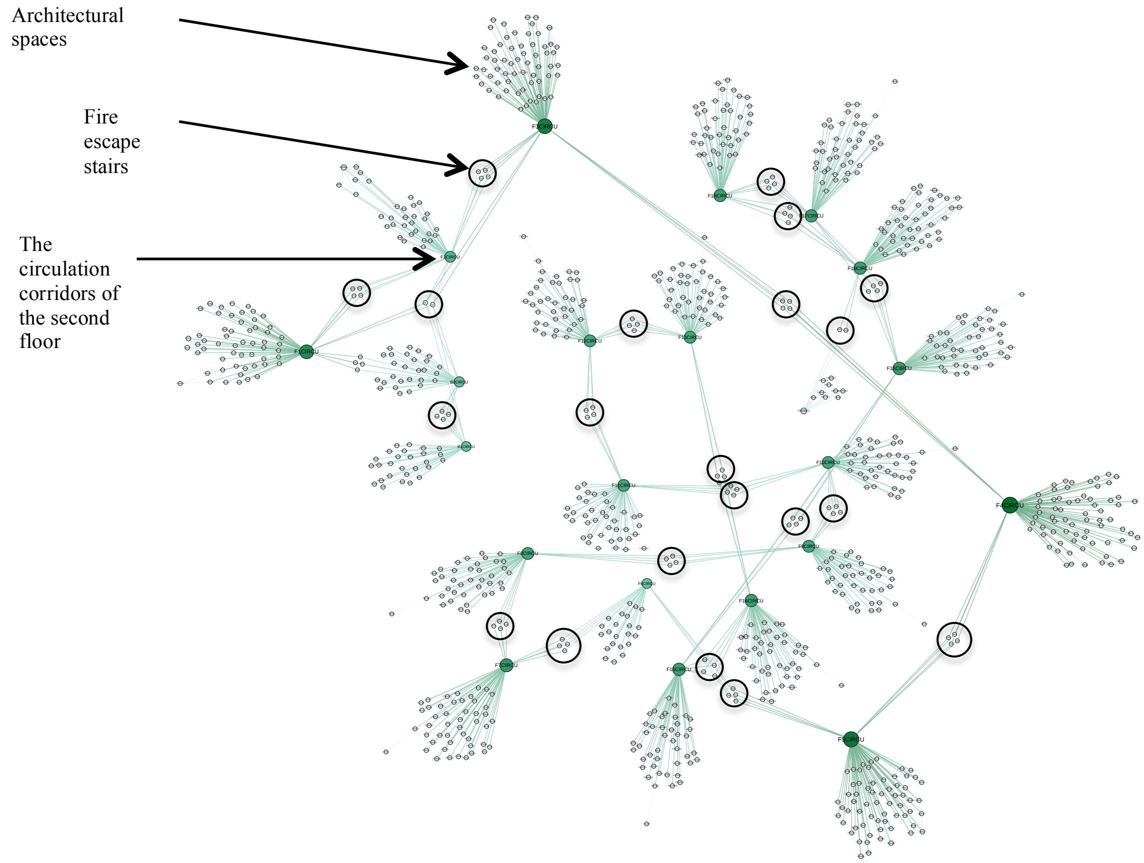

Fig. 10.6 Flow of circulation in case of fire and the location of the fire escapes that link the floors together

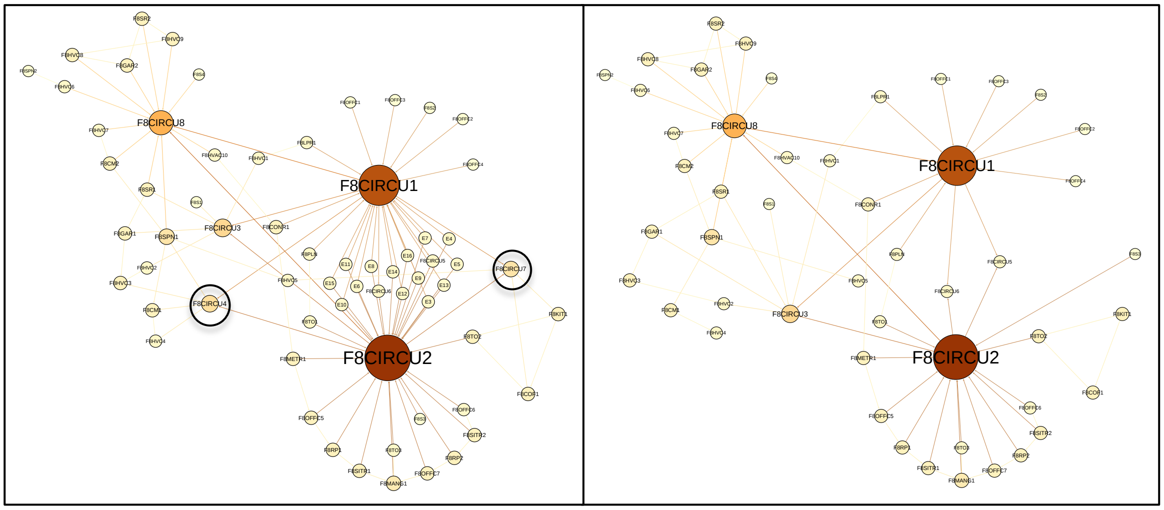

Fig. 10.7 Change of typology on the eighth floor when fire happens in two corridors and they get disconnected from the flow of circulation on the floor

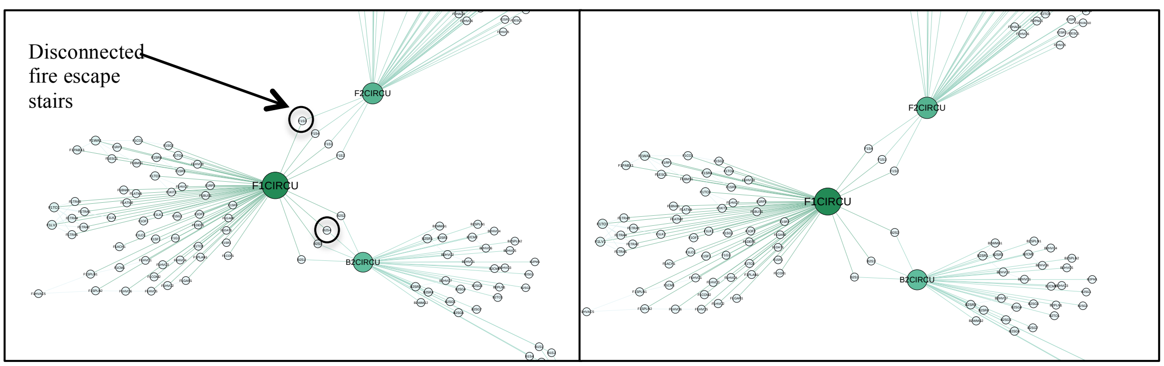

Fig. 10.8 Disconnection of two stairs

Moreover, the research has presented a method of assessing the structural systems in terms of their resilience to earthquakes, demonstrating the propagation of a failure from a certain structural component to other structural components, as shown in Fig. 10.9. The method used in this study can be applied to all building systems to assess the resilience of the system to any failure of one of its components, and the network modelling has indicated the effect and the components that are more affected using the centrality measures.

In conclusion, the use of network analysis has enhanced the ability to model and investigate the design of building systems from the resilience point of view. The previous analysis of the building systems design indicated that modelling the structure and the dynamic of interactions of building systems' components shows very significant findings that can divers the ideas on assessing the resilience of the systems (see chapters 7, 8 and 9). Most building design is required to be resilient to certain phenomena; the use of network analysis and centrality measures will significantly enhance this approach to building design.

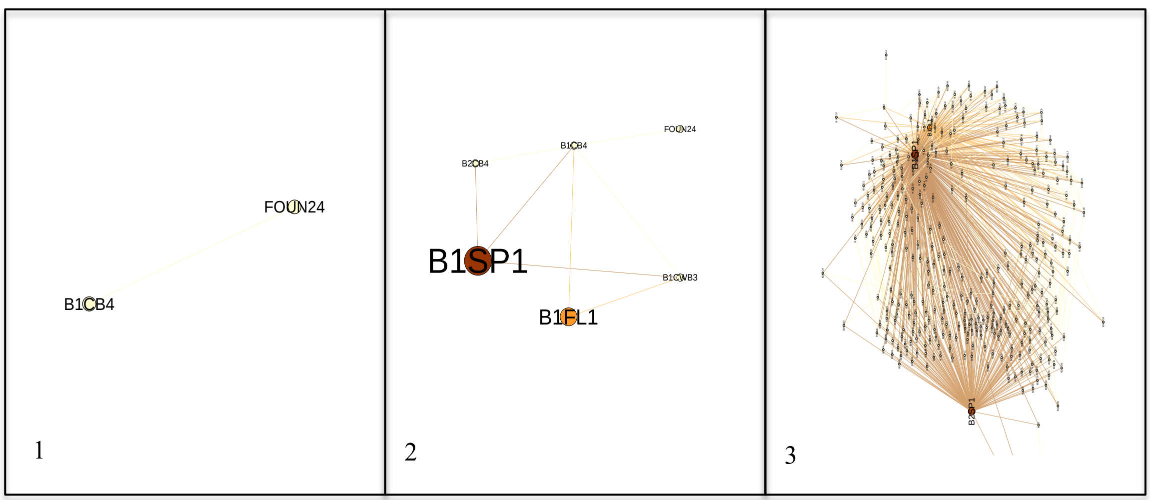

Fig. 10.9 An example of the propagation of the failure of FOUN24, which is foundation number 24 of the building

10.10 Conclusion

The study aimed to uncover the structure and the dynamic of building information interactions and propagation in the building design process and building design product, so this chapter has answered the research questions that significantly help to uncover the complexity of building design. As a result, the chapter has discussed the most important findings of this research, which are the finding of the theoretical framework that captures the complexity of the building design process as well as the complexity of a building as a product. The chapter has indicated the appropriate tools that have been used to model and uncover the complexity of the building design process and building system design. The network modelling and the design structure matrix are very significant tools that are used to model complexity in this research. Moreover, the chapter has discussed the approach of modelling the complexity of the building design process and building systems design. The methods have been presented and discussed, which mainly focused on the connectivity between the three aspects of the building design process and the connectivity between the system components. The chapter has reviewed the modelling of the information flow for the whole building design process and indicated the significant finding of its typological characteristics, as well as highlighting the typological characteristics of the architectural design and flow of circulation in the building case study. In addition, the chapter has presented an assessment of the knowledge diffusion in the building design process as well as an assessment of the resilience to changes in and disconnections of the circulation components of the architectural layout design in case of fire.

CHAPTER 11: SUMMARY AND CONCLUSION

11.1 Introduction

This chapter will present the conclusion of the investigation and uncovering of the structure and the dynamic of building information propagation of the building design process and product. The conclusion of the study will present the robustness of the methodology and the research process first. Second, the research objectives will be reviewed with an explanation on how they were achieved. Third, the knowledge the research has contributed will be presented with an explanation of the value of the research contributions to the field of building design. Fourth, the research limitations will be listed. Fifth, the chapter will provide recommendations and suggestions for further research.

11.2 Robustness of the methodology and research process

The adapted research methodology, which is a design research methodology, is presented in Chapter 5 with the research process that has been followed to achieve the aim of this research. The literature review in this research has been used to combine the knowledge on complexity in building design in order to identify the factors that increase this complexity as well as to determine the gaps in the design knowledge that the research aim and objectives are addressing. Case studies into the building design process and building systems design have been used as a method of collecting and extracting data for the study. The method used to model the information interactions and propagation and knowledge diffusion in the building design process has been presented in Chapter 4, which presents a theoretical framework as well as the method of modelling the interactions of building systems and architectural interactions and propagation. The modelling presented five networks of the building design process; each network depicts a building design stage with its typological characteristics, as well as each of the building systems was modelled and presented as a network with its typological characteristics. The study has utilised the network centrality measures to indicate the information flow and knowledge diffusion in the building design process stage, as well as it assesses the importance of the three aspects of the building design process, which are the building design team, tasks, and process components. In addition, the study has utilised the centrality measures of the networks that were generated for each building system to indicate the connectivity between the building system's components, as well as it assesses the resilience of the building system's design and the ability to use the method to improve the ability to design resilient building systems. The network graphs and the centrality measures were generated using Gephi software, and the general characteristics of centrality measures of both the building design process and building systems network were calculated using SPSS. This designed methodology has provided a coherent approach to investigate the complexity of knowledge diffusion and assess the information that flows between the building design process aspects as well as it provides a significant approach to designing building systems to be resilient to any changes and disconnections of components, which are considered as the design phenomena that need to be predicted at an early stage when designing building systems.

11.3 Accomplishing the research objectives

1. To define the concept of complexity science and complexity of design in order to utilise the complexity approach in investigating complexity in the building design process and building design product information and components' interactions.

The complexity science literature review approach is used in this research, which is investigating the complexity of engineering processes and products. This investigation requires a method and techniques for modelling the components and the information about the designed product. The achievement of this objective has been established in Chapter 2, which reviews the complexity science approaches to investigating complexity in different fields of science. In addition, it reviews the previous studies of complexity in the building design process and building design product, which significantly helped the study to capture the factors that increase the complexity in building design, which generated the theoretical framework of factors that increase the complexity of the building design process presented in Chapter 4.

2. To establish a theoretical framework that modelled the complexity of the building design process and building design product in the form of factors.

Furthermore, this objective intended to identify the factors that increase the complexity of information flow and knowledge diffusion in the building design process as well as those that increase the complexity of designing building systems that are resilient to change and disconnection of system components. The establishment of this objective has been addressed by reviewing the literature on complexity in building design and modelling the factors that increase the complexity. In addition, the theoretical approach required to model the aspects of building design process knowledge diffusion interactions, which are the design team, tasks, and components, was determined. Moreover, the theoretical approach necessary to model the interactions between building architectural spaces and building systems components' interactions according to the function of each of the systems components was established.

3. To establish a coherent design research methodology designed for the research problem as a process of modelling and assessing the networks generated for the building design process and building systems design.

This objective was established by reviewing the literature on complexity modelling and determining the process of investigating the complexity of building process knowledge diffusion and building design product. In addition, the process was designed to uncover the typological characteristics of their models and uncover the approach required to assess the significant aspects of the knowledge diffusion and the resilience of systems' significant components. The use of a design structure matrix has enhanced the ability to determine the interactions and the flow of information between the building design process as well as the building systems design components. Extracting the interactions of the design structure matrix and importing them into network-generating software has significantly uncovered the complex typological characteristics of the building design process as well as building systems design. In addition, the use of centrality measures improved the assessment of knowledge diffusion in the process and the investigation of resilience in building systems design.

4. The uncovering of the complexity of the building design process interactions based on the RIBA plan of work was modelled based on extracting the three aspects of the building design process.

This objective was achieved by extracting the design tasks of each of the building design process stages as nodes in the network of the stage and linking these design tasks to the design team member required to establish the design task. In addition, adding to the network the aspect of the design process component, which is defined as the outcome of the establishment of the design task and linking them to the design tasks required to establish them as well as to the design team member who that contributes to establishing them. This modelling has significantly determined the importance of the design process components in each of the design stages in terms of a whole stage's requirements, as well as it has determined the importance of the knowledge that flows from and to these design process outcomes. This modelling give a significantly clear vision of the importance of each of the design team members and design outcomes in the design stage and provides a view of the knowledge diffusion in the design stage, which will help designers in the design process to predict the effect of undelivered design tasks and design outcomes on the whole design process stage.

5. The uncovering of the complexity of building systems design interactions based on a building case study was modelled based on the designed methodology, which extracted the data from each system's components.

This objective was achieved by extracting each system's interacting components and linking them to the components with which they connected as a node in the building systems networks; for example, extracting the components of the architectural layout by extracting the architectural spaces of the floor plan and linking them to the circulation corridors and generating a network of the circulation flow in the building as well as linking these corridors to the vertical circulations that link the floors' circulation together. Moreover, the research determined the resilience of these networks, which is considered to be a design phenomenon, by assessing the effects of changes and disconnections, such as a fire in a corridor, and determining the alternative fire escapes in the architectural spaces that are close to a fire in the circulation corridor.

11.4 Knowledge contribution

The research has contributed to the existing body of knowledge on building design in the following areas:

1. A comprehensive literature review to identify the gaps in the building design process and design product complexity of modelling and investigating knowledge diffusion and resilience.
2. The compilation of a set of factors that increase complexity of the design process and design product.
3. Classification of the complexity factors in terms of the building design process and building design product.
4. Development of a theoretical framework that captures the complexity of the building design process and product.
5. Determination of the approach for modelling the complexity of information flow and knowledge diffusion in the process and the connectivity in building systems design.

6. Development of an assessment method to uncover the complexity of information flow and knowledge diffusion in the building design process stages.
7. Development of an assessment method to uncover the complexity of building systems design connectivity and assess the resilience of these systems in terms of changes in and disconnections of systems' components.
8. Development of a practical perspective to formalise the modelling decisions of the building design process and building systems design.

11.5 Research limitations

Each research project is developed based on an assumption that it meets the context of the research. This research has been conducted in a specific time period and under certain resource constraints, and so it is no different. In addition, several research limitations have been identified.

1. The modelling of the building design process is based on theoretical aspects of the building design process that were extracted from the RIBA plan of work as a case study; however, the investigation of complexity of the building design process for a specific building design model is required to improve the findings.
2. The modelling of building architectural design and building systems design was based on a building designed for offices and shopping. However, the use of more than one type of building will significantly increase the ability to uncover factors that increase the complexity of designing resilient systems for each type of building.
3. Investigation is limited to one type of building.

4. Building performance is not modelled in the analysis.

11.6 Recommendations and suggestions for further research

The contributions to the knowledge design listed in this chapter work as foundations on which to build future research in the area of investigation of building design complexity. This thesis has identified several areas that would benefit from future research in the field.

1- An investigation and modelling of several case studies and existing building design processes in different types of building, indicating the variety of important factors in the three main aspects of the building design process, which are the design team, design tasks, and design process components

2- An investigation and modelling of several case studies of building architectural and systems design in different type of building, indicating the verities of the importance of resilience to a components of each of the building systems depending on the building's function.

3- Modelling that links the complexity of the building design process to a building product, which requires a case study of specific building design process aspects, such as the design tasks and team and components of process that are linked to the building systems' components.

4- An investigation and modelling of the building design process and building systems design on the building performance.

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Appendix: The codes for the nodes for the aspects of the flowing design process stages

Nodes	ID
Strategic Definitions stage	SDS
Preparation and Brief stage	PBS
Concept Design stage	CDS
Developed design stage	DDS
Technical Design stage	TDS
Business case	BC
Assembling and monitoring the project team	AM
Project program	PP
Previous projects feedback	PF
Strategic brief	SB
Project objectives	PO
Quality objectives	QO
Sustainability strategies	SS
Project budget	PB
Feasibility studies	FS
Site information	SI
Projects roles table	PR
Contractual tree	CT
Handover strategy	HS
Risk assessment	RA
Schedule of services	SS
Design responsibility matrix	DR
Information exchange	IE
Project Execution plan	PE
Research and Development aspects	RD
Construction Strategy	CS
Health and Safety Strategy	HSS
Planning Application	PA
Operational Strategy	OS
Maintenance strategy	MS
Stage Design Program	SP
Final project brief	FPB
Project strategies	PS
Cost information	CI
Concept design	CD
Change control process	CP
Developed design	DD
Building Contract	BCO

Building Regulations Submission	BRS
Technical Design	TD
Client and/or client advisor	C-A
Project lead	PL
Lead designer	LD
Architect	A
Building services engineer	BSE
Civil & structural engineer	CSE
Cost consultant	CO
All additional roles	AR
All roles	AR
Construction lead	CL
Health & safety advisor	HAS
Contract administrator	CA
Initial Project Brief	IPB